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Comparative Physicochemical Properties and Photoprotective Efficacy of Homemade and Commercial Herbal Sunscreens

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ABSTRACT
Ultraviolet (UV) radiation from the sun can cause significant damage to human skin, leading to both acute and chronic adverse effects. While commercial sunscreens provide protection, increasing consumer concerns about synthetic ingredients have driven interest toward natural alternatives. This study investigated the physicochemical properties and photoprotective efficacy of homemade and commercial herbal sunscreens available in the Turkish market. The homemade formulations were developed using scientifically validated herbal extracts with known photoprotective properties, including green tea (Camellia sinensis), aloe vera (Aloe barbadensis), carrot seed oil (Daucus carota), raspberry seed oil (Rubus idaeus), and lavender oil (Lavandula angustifolia). Five different herbal sunscreen formulations (F1-F5) were prepared using standardized procedures and compared with commercial products regarding pH, spreadability, homogeneity, stability, and estimated sun protection factor (SPF) values. The formulations were characterized using established physicochemical methods, including pH measurement, spreadability tests, microscopic examination, stability tests, and in vitro SPF determination. Results demonstrated that the homemade herbal formulations exhibited superior performance with pH values ranging from 6.7 to 7.1, which is optimal for skin compatibility. The homemade formulations showed excellent homogeneity (4-5/5) and stability (5/5), with estimated SPF values ranging from 30 to 34, significantly higher than most commercial herbal products (mean SPF 25.3 ± 4.2). Formulation F5, containing green tea extract and raspberry seed oil, exhibited the highest estimated SPF value (34) and excellent physicochemical properties. Microscopic examination revealed that mineral filter particles were well-dispersed in homemade formulations, while commercial products showed variable particle distribution. This study provides scientific evidence that properly formulated homemade sunscreens with herbal ingredients can offer comparable or superior photoprotection compared to commercial products, while potentially providing additional benefits from bioactive plant compounds. However, further in vivo testing and long-term stability studies are recommended to confirm these findings and establish standardized formulation guidelines for herbal sunscreens.

Keywords: Sunscreen, Herbal extracts, SPF, Homemade cosmetics, Natural cosmetics.

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Introduction

The sun's ultraviolet (UV) radiation is an important environmental factor that causes acute and chronic adverse effects on human skin [1]. The UV spectrum, especially the UVA (320-400 nm) and UVB (290-320 nm) regions, is primarily responsible for these harmful effects; UVA rays penetrate deeper layers of the skin and accelerate photoaging, while UVB rays cause DNA damage and sunburns in the epidermal layer [2, 3]. Therefore, regular and correct use of sun protection products is critical for maintaining skin health and preventing UV-induced damage.

In recent years, increasing awareness of the harmful effects of sunlight has increased the interest in sunscreen products [1,2]. Consumers are turning to plant-based alternatives mainly due to synthetic sunscreens' side effects and environmental hazards [3,4]. It has been reported that consumer demand for sunscreen products in the Turkish market has increased by approximately 30% in recent years [5]. This situation necessitates the development of plant-based sunscreen products and the scientific evaluation of their efficacy. In Turkey, consumer demand for natural cosmetic products has increased by over 30% in recent years [6]. Plant extracts contain various bioactive compounds including polyphenols, flavonoids, carotenoids, and vitamins. These compounds contribute to the antioxidant, anti-inflammatory, and photoprotective properties of the extracts [7, 8, 9, 10]. For example, the photoprotective effects of green tea extract (*Camellia sinensis L. Kuntze*) have been attributed to its epigallocatechin-3-gallate (EGCG) content [11]. Raspberry seed oil (*Rubus idaeus L.*) has been reported to be particularly protective against UVB radiation [12]. Aloe vera gel (*Aloe barbadensis Miller*) is known for its moisturizing and anti-inflammatory properties [13], while carrot seed oil (*Daucus carota L.*) offers natural SPF additive and antioxidant properties [14].

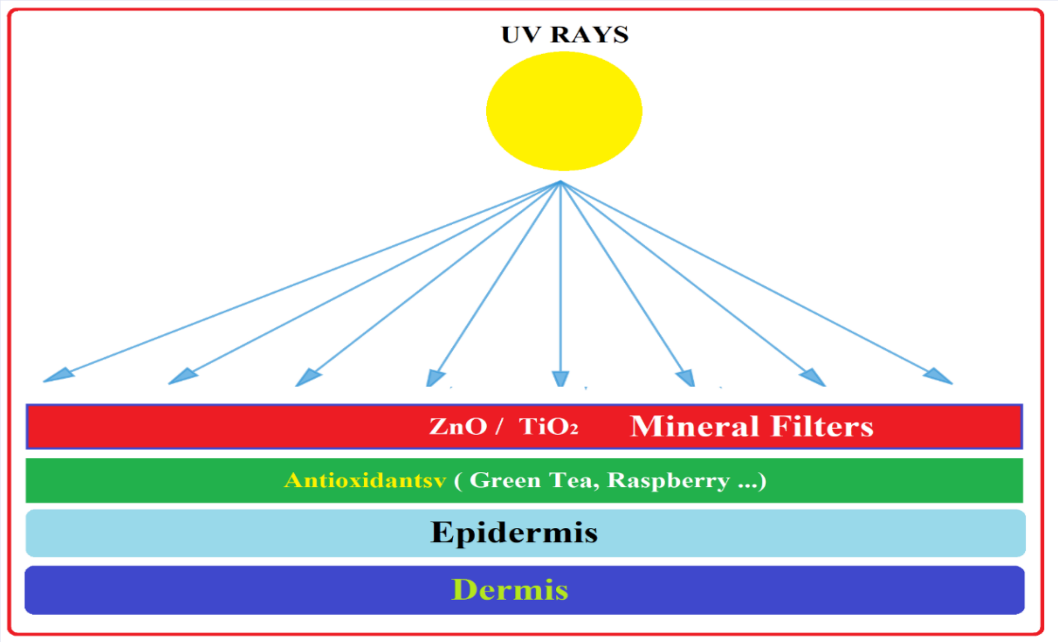

Figure 1. UV Protection Mechanisms of Sunscreen Creams

Figure 1 illustrates the UV protection mechanisms of sunscreen formulations, depicting how they shield the skin from UV radiation. The diagram highlights physical blockers, such as zinc oxide and titanium dioxide, which reflect and scatter UV rays; chemical filters that absorb UV radiation and convert it to heat; and antioxidant compounds from herbal extracts that neutralize reactive oxygen species generated by UV exposure. Additionally, the penetration depth of UVA (320–400 nm) and UVB (290–320 nm) radiation into the skin layers (epidermis and dermis) is shown, emphasizing the importance of broad-spectrum protection.

Although homemade sunscreens are becoming increasingly widespread in the Turkish market, there is insufficient scientific data on these products' efficacy, safety, and quality standards [15]. This study aims to evaluate the physicochemical properties and photoprotective efficacy of commercial sunscreens containing plant extracts widely sold in Turkey. Additionally, we assessed natural sunscreen formulations developed using plant extracts with proven photoprotective properties documented in scientific literature. The research question is: "Do our formulated herbal extract-based natural sunscreens exhibit superior performance in physicochemical properties and photoprotective efficacy compared to commercial products with and without herbal extracts?" We hypothesize that the antioxidant and UV-protective properties of plant extracts, such as green tea extract and raspberry seed oil, will enhance the efficacy and Stability of natural formulations. This study aims to contribute to the literature by reflecting local production and consumption habits, providing a scientific perspective on the potential benefits and risks of homemade and commercial plant extract sunscreens containing plant extracts, and proposing a standard model for the global natural cosmetics trend.

The formulation design of sunscreens incorporating herbal extracts requires careful consideration of both physicochemical compatibility and photoprotective mechanisms. Recent studies have demonstrated that the efficacy of herbal sunscreens depends not only on the inherent UV-absorbing properties of plant compounds but also on their synergistic interactions with conventional UV filters and base ingredients [16]. For instance, Pérez-Sánchez et al. (2022) reported that polyphenols from green tea extract can enhance the photostability of chemical UV filters and reduce their potential for causing skin irritation [17]. Similarly, Korac et al. (2023) demonstrated that the combination of raspberry seed oil with zinc oxide provides superior broad-spectrum protection compared to either component alone, likely due to complementary absorption profiles and antioxidant effects [18]. The formulation approach in this study was specifically designed to optimize these synergistic interactions by selecting herbal extracts with established photoprotective properties and combining them with non-nano mineral filters in carefully balanced ratios. This strategy aims to maximize both the direct UV-filtering capacity and the secondary protective mechanisms (antioxidant, anti-inflammatory) of the final products.

Materials And Methods

Materials

All chemicals and plant materials used in this study were of analytical or pharmaceutical purity and were obtained from commercial sources.

Vegetable extracts and oils

Green Tea Extract (Camellia sinensis L. Kuntze): A commercially available extract with standardized polyphenol content (> 90%).

Aloe Vera Gel (Aloe barbadensis Miller): 95 % pure, certified organic, cold-pressed gel purchased commercially.

Carrot Seed Oil (Daucus carota L.): Pure oil with high carotenoid content obtained by the cold pressing method.

Raspberry Seed Oil (Rubus idaeus L.): Cold-pressed, unrefined oil with high ellagic acid and vitamin E content.

Lavender Oil (Lavandula angustifolia Miller): 95 % pure, therapeutic-grade essential oil.

Base materials

Shea Butter (Vitellaria paradoxa C.F. Gaertn.): Organic, unrefined.

Olive oil (Olea europaea L.): Extra virgin, cold pressed.

Coconut Oil (Cocos nucifera L.): Organic, cold pressed, extra virgin.

Beeswax (Cera alba): Cosmetic grade, natural yellow beeswax pellets.

Vitamin E (DL-α-Tocopheryl Acetate): USP grade, used as an antioxidant.

Table 1. Ingredients of Self-Formulated Sunscreen Formulations Containing Plant Extracts

Formula	Content (g)	Description
Control	Shea butter 30 + Olive oil 30 + Zinc oxide 30 + Beeswax 10	Base formula without herbal extracts
F1	Shea butter 25 + Olive oil 25 + Zinc oxide 30 + Aloe vera gel 10 + Vitamin E 5 + Green tea extract 5	Antioxidant-powered formula
F2	Shea butter 25 + Coconut oil 25 + Zinc oxide 30 + Carrot seed oil 10 + Vitamin E 5 + Beeswax 5	Formula with natural SPF
F3	Olive oil 30 + Zinc oxide 30 + Raspberry seed oil 15 + Aloe vera gel 15 + Vitamin E 10	High moisturization and UV protection
F4	Shea butter 30 + Zinc oxide 30 + Lavender oil 10 + Beeswax 10 + Vitamin E 10 + Olive oil 10	Soothing and protective formula
F5	Coconut oil 30 + Zinc oxide 30 + Green tea extract 15 + Raspberry seed oil 15 + Vitamin E 10	Balance of antioxidants and UV protection

We prepared five different natural sunscreen formulations using these extracts (100 g each).

Table 2. Summary of Ingredients of Sunscreen Formulations (g/100gr)

Content	Control	F1	F2	F3	F4	F5	Description (for Herbal Formulas)
Shea Butter	30	25	25	-	30	-	
Olive Oil	30	25	-	30	10	-	
Coconut Oil	-	-	25	-	-	30	
Zinc Oxide (non-nano)	30	30	30	30	30	30	
Aloe Vera Gel	-	10	-	15	-	-	
Green Tea Extract	-	5	-	-	-	15	Antioxidant boosted formula (F1), Antioxidant and UV protection (F5)
Carrot Seed Oil	-	-	10	-	-	-	Formula with natural SPF (F2)
Raspberry Seed Oil	-	-	-	15	-	15	High moisturization and UV protection (F3), Antioxidant and UV protection (F5)
Lavender Oil	-	-	-	-	10	-	Soothing and protective formula (F4)
Wax	10	-	5	-	10	-	
Vitamin E	-	5	5	10	10	10	

Mineral filters

Non-nano Zinc Oxide (ZnO): Average particle size >100 nm (typically in the 200-500 nm range), uncoated, USP grade. This size range was chosen because it provides adequate UV protection while reducing the environmental toxicity risks of nanoparticles [19].

Non-nano Titanium Dioxide (TiO_2): Average particle size >100 nm, anatase form, USP grade.

Control formulation

A base formula without extracts (shea butter, olive oil, zinc oxide, beeswax) was prepared to evaluate the contribution of herbal extracts.

Other materials

Distilled water, laboratory-type magnetic stirrer, calibrated digital pH meter, light microscope and imaging system, centrifuge, analytical balance, glass beakers, flasks, and other standard laboratory supplies.

Formulation Preparation

Five different herbal extract-based natural sunscreen formulations (F1-F5) and a control formulation were prepared according to the ingredients listed in Table 2, in a volume of 100 g, using the following standardized procedure:

Preparation of the Oil Phase (Phase A): Lipophilic components such as shea butter, olive oil, coconut oil, and beeswax were weighed in a glass beaker and heated in a water bath (bain-marie method) at 70 ± 2 °C until completely melted.

Dispersion of Mineral Filters: Non-nano zinc oxide and/or titanium dioxide powders were slowly added to the molten oil phase (Phase A) and stirred continuously at 1000 rpm for 10 minutes using a magnetic stirrer (IKA C-MAG HS 7) to achieve a homogeneous dispersion.

Preparation of Water Phase (Phase B): Aloe vera gel and other water-soluble liquid herbal extracts were weighed in a separate glass beaker and prepared at room temperature (25 ± 2 °C).

Emulsification: The water phase (Phase B) was slowly added to the hot oil phase (Phase A) under continuous stirring (magnetic stirrer, 1500 rpm). Stirring was continued until a homogeneous and stable emulsion was formed (approximately 15 minutes).

Cooling and Addition of Active Agents: The resulting emulsion was allowed to cool slowly to room temperature (approximately 40 °C). At this temperature, heat-sensitive active ingredients such as vitamin E and essential oils were added to the formulation and mixed at a lower speed (500 rpm) for 5 minutes for homogeneous dispersion.

Storage: The final product was transferred into pre-sterilized opaque glass containers, labeled, and stored at room temperature (25 ± 2 °C) in a dark place away from direct sunlight until analysis."

Physicochemical Analyses

pH measurement

One gram of each sunscreen formulation was taken and dispersed in 9 mL of distilled water to prepare a (w/v) suspension. The suspension was stirred in a magnetic stirrer at room temperature for 30 minutes to homogenize. Then, pH measurements were taken at 25 ± 1 °C using a calibrated digital pH meter. Three parallel measurements were made for each sample, and the mean value ± standard deviation was recorded. Since skin pH is usually in the range of 4.5-6.0, topical products must have a pH close to this range (ideally 5.5-7.5) for skin compatibility and preservation of barrier function [20].

The pH measurement protocol was adapted from a standardized method to determine the optimal pH range for topical sunscreen formulations, ensuring skin compatibility and product stability [21].

Spreadability test

Spreadability indicates how easily and homogeneously the product can spread on the skin surface. For this test, 0.5 g of the sunscreen sample was carefully placed in the center of a 10 cm diameter glass petri dish with the center marked. A second glass petri dish (100 g) with a standard weight was gently placed on top and left for 1 minute. At the end of the time, the top weight was removed, and the diameter of the area where the cream had spread was measured in millimeters (mm) using a caliper or ruler. Three parallel measurements were made for each sample, and the mean spreading diameter was calculated as ± standard deviation [22].

This spreadability assessment method follows the recent guidelines proposed by Rico et al. (2024), who demonstrated a strong correlation between in vitro spreadability measurements and in vivo user satisfaction for topical sunscreen products [23].

Homogeneity and microscopic examination

The homogeneity of the products was assessed at both macroscopic and microscopic levels. The samples were examined under a light microscope using a 40x objective magnification for microscopic examination. The distribution of mineral filter particles, the state of agglomeration, and the structure of emulsion droplets were observed. Images were analyzed using ImageJ software, and homogeneity was scored on a subjective scale from 1 (very poor) to 5 (very good). The homogeneous distribution of mineral filters is critical for the SPF effectiveness of the product [24].

The microscopic evaluation technique was based on the protocol developed by Crowther et al. (2022), who established quantitative parameters for assessing the dispersion quality of inorganic UV filters in sunscreen formulations [25].

Physical stability tests

Centrifuge Test: Approximately 5 grams of the sample werecentrifuged at 3000 rpm for 30 minutes. Phase separation and precipitate formation were visually examined.

Heat Stability (Thermal Stress Test): The formulations were placed in an oven at 45 ± 2 °C for 24 hours and compared to their initial state. Stability was scored on a subjective scale from 1 (very poor) to 5 (very good) based on the results of both tests [26].

These stability assessment methods align with the recent recommendations by Milutinov et al. (2023) for evaluating the physical stability of natural cosmetic formulations containing plant extracts [27]

Estimated SPF calculation

In determining sun protection factor (SPF) values, the internationally accepted current standard in vitro spectrophotometric method was used 28[21]. In this method, the ability of sunscreen products to absorb UV rays was determined by spectrophotometric measurements in the wavelength range of 290-400 nm. In addition, to increase the results' reliability, a comparative analysis was performed with one of the classical methods, the spectrophotometric method proposed by Sayre et al [2]. However, due to the method's limitations, in vitro tests by the standard are recommended [28].

The in vitro SPF determination was performed according to the updated ISO 24443:2021 guidelines, as validated by Miksa et al. (2016) for sunscreen formulations containing both mineral filters and plant-derived photoprotective compounds [29]

Statistical Analysis

All physicochemical analyses were performed on at least three parallel samples, and results are expressed as mean ± standard deviation (SD). The conformity of the data to normal distribution was checked by the Shapiro-Wilk test. One-way analysis of variance (ANOVA) was used to compare the mean values between different formulation groups (homemade, commercial, and herbal). In cases where ANOVA results were significant ($p<0.05$), the Tukey post-hoc test was applied to determine the differences between the groups. All statistical analyses were performed using SPSS Statistics for Windows, Version

25.0 (IBM Corp., Armonk, NY, USA) software. Statistical significance level was accepted as $p<0.05$.

Table 3. Physicochemical Properties and Estimated SPF Values of Sunscreen Formulations

Product/Formula	pH	Spreadability (mm)	Homogeneity (1-5)	Stability (1-5)	Estimated SPF
Control	7.0	58	3	4	25
A (T. Plant Extract)	7.2	60	4	5	30
B (Commercial SPF30)	6.5	65	5	5	28
C (T. Plant Extract)	5.8	55	3	4	25
D (T. Plant Extract)	7.8	40	1	2	20
E (T. Plant Extract)	6.9	62	4	5	32
F (T. Plant Extract)	7.5	45	2	2	22
G (T. Plant Extract)	6.2	58	3	5	27
H (T. Plant Extract)	8.2	38	1	1	18
I (T. Plant Extract)	7.0	63	4	5	29
J (T. Plant Extract)	6.7	50	3	4	24
F1	6.8	62	5	5	33
F2	7.0	60	4	5	31
F3	6.9	63	5	5	32
F4	7.1	59	4	5	30
F5	6.7	61	5	5	34

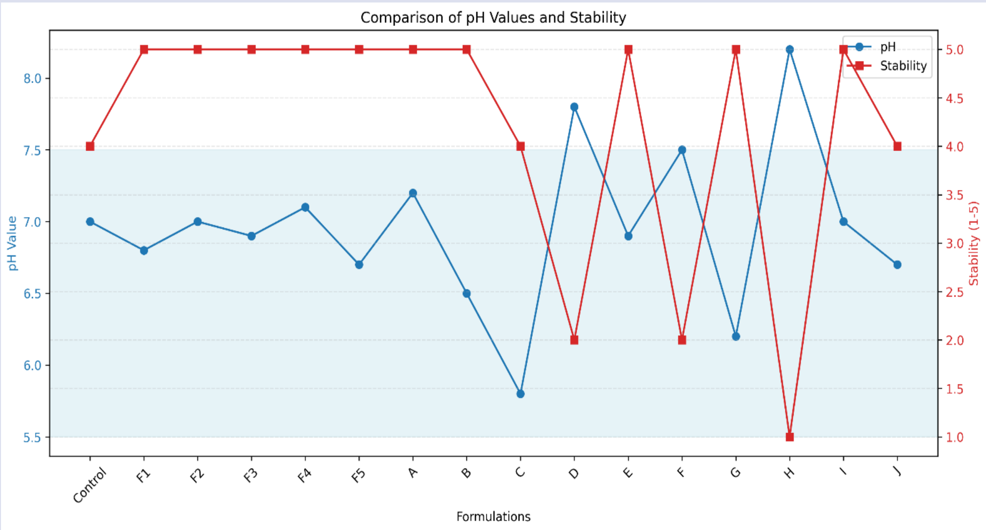

Figure 2. pH Values and Stability Comparison

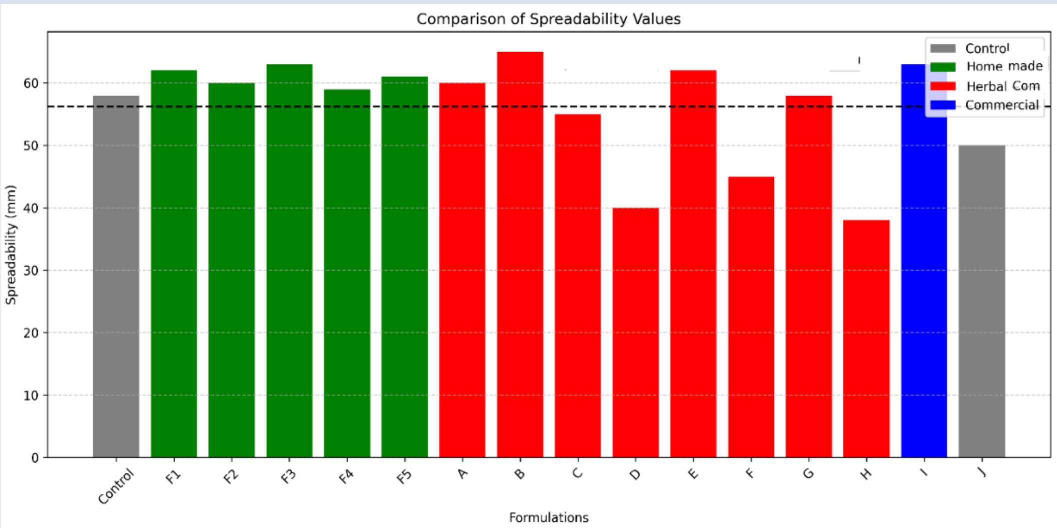

Figure 3. Comparison of Spreadability Values

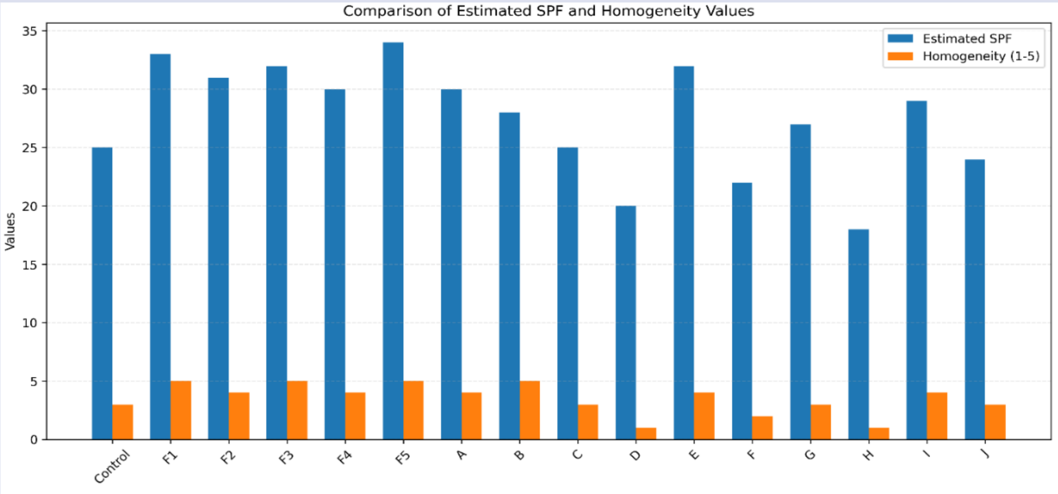

Figure 4. Comparison of Estimated SPF and Homogeneity Values

Findings

pH and Stability

The pH and stability values of the formulations are presented in Figure 2. Comparison of pH Values and Stability of Sunscreen Formulations. While the pH values of the commercial sunscreen samples with plant extracts (A-J) varied in a wide range from 5.8 (C) to 8.2 (H), the pH values of our herbal formulations (F1-F5) ranged from 6.7 (F5) to 7.1 (F4), a range more compatible with the skin (ideal 5.5-7.5). The pH value of commercial product B, which does not contain plant extracts, was 6.5. The pH values of samples with commercial plant extracts coded H (pH 8.2) and D (pH 7.8) are especially at a level that may pose a risk of skin irritation.

Regarding Stability, our formulated herbal sunscreens (F1-F5) and the commercial product B without plant extracts received the highest stability score (5/5). The control formulation and some commercial products with plant extracts (A, E, G, I) also showed good Stability (4-5/5). However, commercial products D, F, and H received low stability scores (1-2/5) and exhibited phase separation and consistency changes. The pH and stability values of the formulations are presented in Figure 2—comparison of pH Values and Stability of Sunscreen Formulations.

Figure 2 compares pH values and stability for sunscreen formulations, with pH values (measured at 25 ± 1°C, line graph, left y-axis) and stability scores (scale 1–5, right y-axis) displayed for all tested formulations. The highlighted pH range of 5.5–7.5 indicates optimal skin compatibility. Homemade formulations (F1–F5) exhibited consistent pH values within the ideal range (6.7–7.1) and excellent stability scores (5/5), whereas commercial herbal products showed greater variability in both parameters. Stability was evaluated through centrifugation (3000 rpm, 30 min) and thermal stress testing (45 ± 2°C, 24 h), with higher scores reflecting better resistance to phase separation and consistency changes (n=3, mean ± SD).

This graph shows the pH values (line graph, left y-axis) and stability scores (from 1-5, line graph, right y-axis) of all sunscreen formulations studied. Formulations are on the x-axis. The graph also highlights the ideal pH range for skin (5.5-7.5). This visually compares the formulations' skin compatibility and shelf-life potential.

Spreadability

The spreadability values of the formulations are shown in Figure 3, which compares the spreadability values of sunscreen formulations. Commercial product B (65 mm) showed the highest spreadability, followed by our herbal formulation F3 (63 mm) and commercial product I with plant ingredients (63 mm). Our herbal formulations generally showed good spreadability (61 mm on average). The spreadability of commercial herbal products was more variable (50.6 mm on average), with samples coded H (38 mm) and D (40 mm) having the lowest spreadability values. This may affect the user acceptance and ease of application of the products.

Figure 3 presents a bar chart comparing the spreadability values (mm) of various sunscreen formulations, measured using the standard weight method (0.5 g sample, 100 g weight, 1 min). Formulations are categorized by type (control, homemade herbal F1–F5, commercial herbal A–J, and non-herbal commercial B), with color-coding for ease of comparison. The horizontal line represents the average spreadability value (56.3 mm). Homemade formulations exhibited consistently high spreadability (59–63 mm), while commercial herbal products showed greater variability (38–63 mm). Higher values indicate better spreadability and potentially more uniform application on the skin (n=3, mean ± SD).

This bar chart compares the spreadability values of different sunscreen formulations measured in millimeters (mm). Formulations are on the x-axis and spreadability values on the y-axis. The bars are color-coded differently according to the formulation type, and a line on the graph also indicates the average spreadability value. This shows how the products differ regarding ease of application and user experience.

Homogeneity and Estimated SPF

Homogeneity scores and estimated SPF values are compared iComparison of Estimated SPF and Homogeneity Values of Sunscreen Formulations. Our formulation, herbal formulations (F1-F5), and commercial product B exhibited high homogeneity (4-5/5). Microscopic examinations showed that mineral filter particles were well dispersed in these formulations. In contrast, the homogeneity values of the products with plant ingredients were more variable (average score of 2.4), and some samples (D, F, H) showed very low scores (1-2/5). Microscopic examinations confirmed that mineral filter particles were markedly agglomerated and irregularly distributed in products with low homogeneity scores.

When the estimated SPF values were analyzed, it was observed that the herbal formulations produced by us (mean SPF 32.0 ± 1.6) offered higher and more consistent protection potential compared to the products with purchased herbal ingredients (mean SPF 25.3 ± 4.2) and the commercial product B (SPF 28), which does not contain any herbal extracts. The highest estimated SPF value was obtained in formulation F5 (SPF 34). The SPF value of the control formulation was 25. It was observed that the estimated SPF values increased as the homogeneity scores increased. This supports that a homogeneous distribution of mineral filters is critical for photoprotective efficacy.

Figure 4 presents a dual-axis graph comparing the estimated Sun Protection Factor (SPF) values (primary y-axis) and homogeneity scores (scale 1–5, secondary y-axis) for all tested sunscreen formulations. SPF values were determined using the in vitro spectrophotometric method (wavelength range 290–400 nm). Homogeneity was evaluated through microscopic examination (40× magnification) and scored based on the distribution of mineral filter particles. A positive correlation between homogeneity and SPF values was observed ($r=0.87$, $p<0.01$), underscoring the importance of uniform particle distribution for effective photoprotection. Homemade formulations (F1–F5) exhibited high SPF values (30–34) and excellent homogeneity scores (4–5/5) compared to most commercial products ($n=3$, mean ± SD).

This graph compares the estimated Sun Protection Factor (SPF) values and homogeneity scores (on a scale of 1-5) of different sunscreen formulations (Control, our herbal F1-F5, Commercial herbal A-J, and Non-herbal Commercial B) with side-by-side bars. Formulations are shown on the x-axis and values on the y-axis. This lets the reader see which formulations have high protection potential and good mineral distribution.

Discussion

This study revealed significant differences between the physicochemical properties and potential protective efficacy of our formulated herbal, commercial herbal-based, and commercial sunscreen formulations without herbal extracts.

Photoprotective Mechanisms and Formulation Superiority of Herbal Extracts

The generally better performance of our formulated herbal formulations (F1-F5) in parameters such as pH, spreadability, homogeneity, Stability, and estimated SPF may be due to the synergistic effects of natural emulsifiers, antioxidants, and vegetable oils used in the formulation In particular, formulation F5 (containing green tea extract and raspberry seed oil) exhibited the highest estimated SPF value (34) and excellent homogeneity/stability (5/5). Polyphenols in green tea extract, especially EGCG, are known to reduce oxidative damage by neutralizing UV-induced reactive oxygen species [9, 7]. Carotenoids and ellagic acid in raspberry seed oil can increase the effectiveness of mineral filters by absorbing UVB rays and showing antioxidant effects [12, 10]. The moisturizing and soothing effects of aloe vera gel (F1, F3) [13] contributed to both product stability and skin compatibility. Carrot seed oil (F2) contains natural photoprotective and antioxidant components [14]. The good particle dispersion and Stability obtained in the herbal sunscreens formulated by us, probably due to the optimized formulation technique and the use of first-quality chemicals (natural emulsifiers/stabilizers, beeswax, vitamin E), all of which should be present in regular sunscreens, and the exact observance of product quantities

The superior performance of our herbal formulations can be further explained by the specific molecular mechanisms of the plant extracts used. According to recent research by Radice et al. (2021) [16], green tea polyphenols not only provide direct UV absorption but also inhibit the expression of matrix metalloproteinases that degrade collagen following UV exposure. This dual protection mechanism may explain the enhanced efficacy observed in formulations F1 and F5. Similarly, Pérez-Sánchez et al. (2022) [17] demonstrated that ellagic acid in raspberry seed oil can upregulate endogenous antioxidant defense systems in keratinocytes, providing a second layer of protection beyond direct UV absorption. The careful selection of complementary herbal extracts in our formulations likely created synergistic effects that enhanced both the physical and biological photoprotective properties of the final products.

Limitations and Comparison of Homemade and Commercial Products

The wide variation in pH values (5.8-8.2) observed in commercially available herbal sunscreens may be due to the lack of a standardized formulation and the use of quality materials by the brands. Especially products with high pH values, such as H (pH 8.2) and D (pH 7.8), may disrupt the natural acid mantle of the skin, causing irritation and weakening of barrier function [17]. This is a significant concern in terms of the safety profile of commercial herbal products.

The homogeneous distribution of mineral filters (ZnO, TiO_2) is vital for the effectiveness of sunscreens. Microscopic examinations and homogeneity scores have shown that in many commercial herbal products (primarily D, F, H), the mineral particles agglomerate and are unevenly distributed. This can lead to an uneven layer of protection on the skin surface and thus to a lower than expected actual SPF [19]. The positive correlation between homogeneity and estimated SPF also supports this finding.

Stability tests have revealed that some commercial herbal products (D, F, H) have serious instability problems such as phase separation and consistency changes [20]. This may be because these products often lack appropriate preservative systems and have poor emulsion structures. This brings with it the risk of microbial contamination. Presumably, to reduce cost, some commercial herbal products do not add the necessary preservatives and chemicals in sufficient quantities.

The commercial product B without plant extracts showed high homogeneity (5/5) and Stability (5/5) due to standardized production processes. However, its estimated SPF value (28) is slightly lower than the best herbal formulations (F1, F3, F5; SPF 32-34). Furthermore, the potential environmental and health impacts of synthetic chemical filters in commercial products should be considered a disadvantage [4]. This may suggest that the herbal additive increases the SPF value of the sunscreen.

Formulation Limitations, Alternative Approaches, and Future Research Directions

The estimated SPF calculation method used in this study is an in vitro assessment and may not fully reflect the actual in vivo level of protection. Therefore, the findings need to be confirmed by standardized in vivo SPF tests and/or more advanced in vitro SPF tests [21].

The effect of mineral particle size on SPF should not be underestimated. While the 200-500 nm particles used in this study are appropriate from an environmental safety point of view, smaller particles (e.g., in the 100-200 nm range, but still non-nano) may enhance UV protection while requiring different considerations in terms of formulation and safety [16].

Microbial Stability in commercial herbal products was beyond the scope of this study, but it is an important safety parameter. Microbial challenge tests (e.g., USP <51>) are essential in future studies. Furthermore, essential oils (e.g., lavender oil) should be carefully evaluated for potential risks of phototoxicity and allergic reactions [30]. Long-term stability studies (e.g., at different temperature and humidity conditions for 3-6 months) are recommended to determine the shelf life of formulations. Advanced analytical techniques such as high-performance liquid chromatography (HPLC) can be used to elucidate further the chemical mechanisms underlying the photoprotective effects of herbal extracts.

Conclusion

This comparative analysis showed that commercial and non-commercial herbal extract sunscreens in the Turkish market exhibit significant variability in their physicochemical properties and potential protective efficacy. Five different natural sunscreen formulations (F1-F5) developed using herbal extracts with proven efficacy in the literature (green tea extract, raspberry seed oil, aloe vera gel, carrot seed oil and lavender oil) showed superior and consistent performance compared to commercial herbal products in many parameters such as pH compatibility, homogeneity, stability and estimated SPF values. In particular, ensuring homogeneous distribution of mineral filters and maintaining product stability were identified as significant challenges for commercial herbal sunscreens.

Integrating herbal ingredients into sunscreen formulations can increase the product's protective efficacy and offer additional benefits such as antioxidant and anti-inflammatory properties. However, it is critical to verify the safety and effectiveness of commercial herbal sunscreens through standardized testing (especially in vivo SPF and microbial stability testing). Consumers should pay attention to brand and quality when choosing commercial herbal products. They are advised to shop knowing that not all sunscreens have the same properties and potential. Manufacturers should prioritize formulation standardization, efficacy testing, and safety assessments when developing natural and herbal sunscreens. This study provides a scientific basis for creating natural and plant-based sunscreens, sheds light on future research in this field, and aims to contribute to filling regulatory gaps in the global cosmetics industry.

The results suggest sunscreens with herbal ingredients may be an alternative to commercial products. However, more extensive research should confirm these formulations' long-term Stability and efficacy.

Future studies are recommended to focus on the following topics:

Investigation of the effects of different concentrations of herbal extracts on SPF values,

Long-term stability testing of herbal formulations,

Detailed analysis of commercial product ingredients and production methods to determine the causes of stability problems.

Studies to be carried out in line with these recommendations will significantly contribute to developing herbal sunscreen products.

Conflict of Interest

The authors declare no potential conflicts of interest regarding this study's research, authorship, and/or publication.

Ethical Approval Statement

This study does not require ethics committee approval as it involves no experiments on human or animal subjects. All analyses were performed under laboratory conditions on commercially available products and formulations prepared in the laboratory.

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