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Formulation of a Multifunctional Rose Water-Based Anti-Pollution Sunscreen and Makeup Setting Mist

Raz Nur Natasha Abdul Razak[1], Angzzas Sari Mohd Kassim[1]*,

1 *Department of Chemical Engineering Technology, Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, 84600 Pagoh, Johor, MALAYSIA*

*Corresponding Author: Angzzas@uthm.edu.my
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Abstract

Urban environments expose skin to multiple stressors, including ultraviolet (UV) radiation and airborne pollutants, which accelerate oxidative damage, inflammation, and premature skin ageing while compromising the skin barrier. Although daily photoprotection is essential, many existing sunscreen products lack multifunctionality and fail to adequately address pollution induced skin stress or meet consumer demand for lightweight, skin-compatible formulations. This study aimed to develop and evaluate a rose water–based anti-pollution sunscreen and makeup setting mist incorporating botanical antioxidants from Rosa damascena petals and Camellia sinensis leaves. Bioactive compounds were extracted using ultrasound-assisted aqueous extraction with Moringa oleifera coagulant and ultrasound-assisted hydroethanolic extraction. Antioxidant and anti-inflammatory activities were assessed using DPPH radical scavenging and bovine serum albumin (BSA) protein denaturation assays. Selected extracts were incorporated into sprayable mineral-based sunscreen mist formulations containing zinc oxide, optimised using Design of Experiments (DoE), and evaluated for sun protection efficacy using the Mansur spectrophotometric method. Ultrasound-assisted hydroethanolic extraction produced clearer and more homogeneous extracts with higher bioactivity values, attributed to enhanced recovery of polyphenolic compounds. The extracts exhibited significant antioxidant and anti-inflammatory potential, with DPPH inhibition of up to 72.21% for Rosa damascena and 78.29% for Camellia sinensis, and BSA protein denaturation inhibition reaching 66.38% and 78.94%, respectively. DoE optimisation demonstrated that physicochemical stability and uniform dispersion of mineral UV filters were critical for sun protection efficacy, with formulations R9 (≈37 SPF) and R8 (≈31 SPF) showing the best overall performance. Overall, the findings demonstrate that rose water combined with botanical antioxidants can be effectively formulated into a multifunctional facial mist providing UV protection, mitigation of pollution-related oxidative stress, and cosmetic setting performance, supporting its potential as an innovative and consumer-aligned cosmeceutical solution for urban skin protection.

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1. Introduction

Human skin is continuously exposed to various environmental stressors, particularly in urban environments [1]. UV rays from the sunlight, tiny particulate matter (PM), and high-energy visible light (HEVL), or blue light, are the culprits influencing our skin health [1]. They are associated with oxidative stress, inflammation, aging symptoms, and the degradation of the skin barrier. UVA and UVB are widely known for their photoaging and DNA damage; meanwhile, fine particulate matter (PM2.5) can penetrate the surface of the skin and induce lipid damage [1] [2].

Moreover, there is a growing consumer demand for multifunctional products that offer convenience by delivering hydration, sun protection, and cosmetic enhancement in a single product [3]. In addition, the safety and impact of the environment concerning chemical UV filters have resulted in consumers seeking products with mineral sunscreens, which are made from zinc oxide (ZnO) or titanium dioxide (TiO_2). This research is imperative in bridging the gap that exists between the scientific developments in understanding of environmental skin damage and the market's need for effective, convenient, natural, and multifunctional "clean beauty" solutions [3].

Most of the existing cosmetic products on the market are purely designed to counter the UV rays only without addressing the cumulative and synergistic activity of urban pollution and blue light exposure. The conventional commercial spray products containing chemical filters are usually linked to dermatitic reactions on the skin as well as damage to the environment [4]. There are gaps in research on incorporating extensively validated botanicals like *Rosa damascena* and *Camellia sinensis* as antioxidants within the mineral spray sunscreen formulation itself.

The primary aim of this research was to develop and evaluate a multifunctional rose water-based sunscreen and makeup setting mist that utilises botanical antioxidants for comprehensive skin protection. To achieve this, the study first focused on extracting bioactive compounds from *Rosa damascena* petals and *Camellia sinensis* leaves using two advanced ultrasound-assisted methods: aqueous extraction with *Moringa oleifera* as a natural coagulant and hydroethanolic extraction. Subsequently, the second objective involved assessing the biofunctional properties of these extracts through the 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging assay for antioxidant activity and the bovine serum albumin (BSA) protein denaturation assay for anti-inflammatory potential [5][6]. Finally, the research aimed to formulate and optimise the multifunctional mist by integrating these botanical extracts with mineral UV filters, specifically zinc oxide, using a Design of Experiments (DoE) approach [7]. This final objective included evaluating the sun protection efficacy of the resulting formulations through the determination of their Sun Protection Factor (SPF) using the Mansur spectrophotometric method to ensure a minimum level of SPF 30.

2. Literature Review

Urban skin exposure to ultraviolet radiation and airborne pollutants has been highlighted as a major risk factor for oxidative stress, inflammation, and accelerated skin ageing. Exposure of human skin to fine particulate matter PM2.5 and high-energy visible light has been proven to lead to lipid peroxidation and inflammation in the skin [1, 2]. Antioxidants derived from botanical sources, like *Rosa damascena* and *Camellia sinensis,* showed substantial radical scavenging activities and anti-inflammatory properties owing to their substantial content of polyphenols and flavonoids [10, 11]. These are believed to reduce oxidative stress and provide a protective effect from environmental damage, making them ideal for creating multi-functional cosmetic products. Recent studies have also pointed out that consumers' interest is shifting towards multi-functioning cosmetic products with photoprotecting, moisturising, and anti-pollutant properties in a single application [3]. Mineral sunscreen bases, including zinc oxide and titanium dioxide, are being favoured for their photostability and environmental safety versus chemical UV absorbers. However, there is limited research on incorporating established botanical antioxidants into effective application forms, such as sprayable mineral sunscreens. In addition, most literature on SPF values is carried out in vitro, which should be validated by in vivo or ex vivo models [12,13]. Thus, this study is aimed at the design, development, and evaluation of an effective multifunctional rose water-based sunscreen mist using antioxidants, with emphasis on efficiency, biofunctionality, and in vitro sun protection factors.

3. Methodology

This chapter describes the extraction, formulation, and evaluation of a multifunctional facial mist incorporating rose-derived bioactives, mineral UV filters, and plant-based antioxidants. Bioactive ingredients were prepared using ultrasound-assisted extraction methods, with *Rosa damascena* petals processed via aqueous ultrasonication to obtain rose hydrosol and *Camellia sinensis* leaves extracted to yield polyphenol-rich antioxidants. Extracts were subsequently evaluated for antioxidant activity and formulation compatibility. Formulation development involved the incorporation of non-nano zinc oxide and titanium dioxide as mineral UV filters, together with

botanical extracts and film-forming agents, to produce a stable, sprayable emulsion suitable for facial mist application. Product efficacy was assessed through in vitro sun protection factor (SPF) determination using spectrophotometric methods. Antioxidant capacity evaluation via DPPH radical scavenging assay, and anti-inflammatory activity analysis using the bovine serum albumin (BSA) protein denaturation assay. Cosmetic performance was evaluated based on makeup-setting ability, skin feel, non-tackiness, and compatibility with commonly used cosmetic products. All formulation steps were conducted in accordance with clean beauty principles, halal formulation requirements, and dermatological safety considerations.

3.1 Materials

Rosa damascena petals (APS Flora, Malaysia), *Camellia sinensis* (Qiu Xiang Tea, Malaysia), *Moringa oleifera* seed (Zhiwei Herd, Malaysia), xanthan gum (Sigma-Aldrich, USA), polyglyceryl-4 oleate (Future Food, Malaysia), glycerin (Chemiz, Malaysia), sodium citrate (Sigma-Aldrich, USA), citric acid (Sigma-Aldrich, USA), phenoxyethanol & ethylhexylglycerin (Future Food, Malaysia), ethanol (Merck Millipore, USA), BSA (Sigma-Aldrich, USA), phosphate buffered saline (Sigma-Aldrich, USA), DPPH reagent (Sigma-Aldrich, USA), methanol (Sigma-Aldrich, USA), aspirin (Casprin, Malaysia), and ascorbic acid (Sigma-Aldrich, USA).

3.2 Raw Material Preparation

Fresh *Rosa damascena* petals were thoroughly washed to remove any pesticide or contaminants before being gently patted dry and oven-dried at 40 °C for 24 hours. The dried rose petals and dried green tea leaves were then ground to a fine powder using an analytical grinder. Both powders were then stored in an airtight container in the refrigerator.

Moringa oleifera (MO) seeds were prepared by cracking the seed shells using a pestle and mortar. The kernels were gathered and further crushed using a pestle and mortar before being transferred to a tray for oven drying at 50 °C for 24 hours. Dried seeds were ground into a fine powder and placed in three extraction thimbles for the defatting process using Soxhlet. Ethanol was used for the extraction solvent. After 7 hours of extraction at 75 °C, the oil-rich ethanol was discarded, and the defatted moringa kernel cake underwent a second drying process for 12 hours.

The dried moringa kernel cake was used as a natural coagulant by mixing 100 ml of 1.0 M NaCl solution with 100 g of dried MO and stirring for 30 minutes and then vacuum filtering using Whatman No. 1 filter paper. The filtrate was collected as the natural coagulant extract and stored at 4 °C prior to the botanical extract clarification phase.

3.3 Raw Material Extraction

3.3.1 Ultrasound-Assisted Aqueous Extraction Using *Moringa oleifera* Coagulant

To start this extraction method, 73 g of both rose petal powder and green tea powder were weighed and mixed with 1000 ml of distilled water. These solutions were stirred using a glass rod for 10 minutes before being ultrasonicated using a 12 mm titanium probe. The ultrasonication process lasted for 30 minutes, while the temperature was kept at around 83 °C, and the amplitude used was 77%. After the ultrasonication process, the solutions were then filtered using a cloth mesh to remove big clumps of rose and green tea powder. The filtered solutions were then mixed with 20 ml of *Moringa oleifera* extracts and underwent a jar test coagulant procedure. Coagulation was carried out using two distinct stirring phases; first, it was mixed rapidly at 150 rpm for 5 minutes, and then at 30 rpm for 30 minutes. After mixing, the samples were allowed to settle for 40 minutes to allow floc formation and sedimentation. After coagulation and sedimentation, the treated rose and green tea samples were transferred into centrifuged tubes. The samples were centrifuged at 8000 rpm for 20 minutes to remove fine suspended solids. The clear supernatant obtained was collected as clarified rose and green tea extracts for subsequent analysis. These sample solutions were kept in a dark bottle at 4 °C.

3.3.2 Ultrasound-Assisted Hydroethanolic Extraction Method

This procedure was conducted for both *Rosa damascena* and *Camellia sinensis.* This method used a material-to-solvent ratio of 1:40 (w/v), whereby 1 g of plant powder was mixed with 40 ml of 71% ethanol. The sample powder was left to be fully submerged in the solvent for 5-10 minutes. Then the solutions were ultrasonicated for 25 minutes at 55% amplitude. Post-extraction process, the mixture was filtered through mesh cloth and underwent centrifugation at 3000 rpm for 20 minutes to sediment solid particles. The supernatant extracts were transferred to a tinted bottle and stored at 4 °C.

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3.4 Characterisation of Biofunctional properties in extracts

3.4.1 Determination of Antioxidant Activity (DPPH Assay)

DPPH assay was selected for evaluating antioxidants in a sunscreen and makeup setting mist with botanical antioxidants due to its simplicity, sensitivity, and suitability for measuring the free radical scavenging capacity of botanical biofunctional properties. The DPPH working solution was prepared by dissolving 3.9 mg of DPPH powder in 100 mL of methanol to obtain a 0.1 mM solution. For the antioxidant assay, 1.0 mL of the test sample was mixed with 2.0 mL of the DPPH working solution and incubated in the dark at room temperature for 30 minutes. After incubation, absorbance was measured at 517 nm using a UV–visible spectrophotometer. A standard calibration curve was constructed using ascorbic acid as the reference standard, and the antioxidant activity of the formulation samples was determined from the standard curve and expressed as ascorbic acid equivalent (AAE). All analyses were performed in triplicate to ensure accuracy and reproducibility of the results. The percentage inhibition of protein denaturation was calculated using the formula:

$$\%\ Inhibition\ = \left(\frac{Acontrol - Asample}{Acontrol}\right) x\ 100 \quad (1)$$

where $A_{control}$ = absorbance of control and

A_{sample} = absorbance of sample

3.4.2 Determination of Anti-Inflammatory Activity (BSA Protein Denaturation Assay)

In this study, the bovine serum albumin (BSA) protein denaturation assay was selected to assess the anti-inflammatory potential of the sunscreen formulation due to its simplicity, reproducibility, and suitability for preliminary evaluation of anti-inflammatory properties in cosmetic formulations. A 1% (w/v) BSA solution was prepared in phosphate-buffered saline (PBS, pH 6.4–7.4), and test samples were prepared to obtain the required concentrations expressed in mg/mL. The reaction mixture was incubated at 37 °C for 20 minutes, followed by heating at 70 °C for 5 minutes to induce protein denaturation, and absorbance was measured at 660 nm using a UV–Visible spectrophotometer. Anti-inflammatory activity was calculated as the percentage inhibition of protein denaturation relative to the control. A standard calibration curve was constructed using aspirin as the reference standard, and the anti-inflammatory activity of the formulation samples was expressed as mg aspirin equivalent (AE) per mL. All analyses were performed in triplicate to ensure accuracy and reproducibility of the results. The percentage inhibition of protein denaturation was calculated using the formula:

$$\%\ Inhibition\ = \left(\frac{Acontrol - Asample}{Acontrol}\right) x\ 100 \quad (2)$$

where $A_{control}$ = absorbance of control and

A_{sample} = absorbance of sample

3.5 Formulation of a Rose Water-Based Anti-Pollution Sunscreen and Makeup Setting Mist

The chosen formulation strategy for this sunscreen mist is defined as a stabilised aqueous suspension, an approach that prioritises a lightweight, water-based formulation while maintaining the high mineral content necessary for UV protection. The ingredients were grouped into 3 phases: phase A, phase B and phase C. Phase A focuses on the structural foundation of the product, while phase B ensuring uniform UV filter dispersion and homogenisation of integrated ingredients, and lastly, phase C involves the incorporation of heat-sensitive ingredients and preservation.

3.5.1 Design of Experiments (DOE)

The Design of Experiments (DOE) approach was applied to develop the sunscreen mist formulation, which enabled the understanding of the impact of selected variables on the final performance of the sunscreen. For optimisation, fractional factorial design 2^{4-1} was used, which was carried out through Design Expert Software (State-Ease Inc., USA). Four functional ingredients were identified as independent variables: zinc oxide, pullulan,

polyglyceryl-4 oleate, and xanthan gum. Table 2.1 presents the Design of Experiments (DOE) matrix for the sunscreen formulation, including the levels of each formulation variable.

Table 1 *Design of Experiments (DOE) matrix for the sunscreen formulation*

Run	ZnO (g)	Pullulan (g)	Polyglyceral-4 Oleate	Xanthan Gum (g)	Water (g)
R1	10.0	1.00	1.00	0.10	78.06
R2	15.0	1.00	1.00	0.40	72.76
R3	10.0	5.00	1.00	0.40	73.76
R4	15.0	5.00	1.00	0.10	69.06
R5	10.0	1.00	5.00	0.40	73.76
R6	15.0	1.00	5.00	0.10	69.06
R7	10.0	5.00	5.00	0.10	70.06
R8	15.00	5.00	5.00	0.40	64.76
R9	12.50	3.00	3.00	0.25	71.42

3.6 Sun Blocking Ability Analysis (Sun Protection Factor)

Sun-blocking ability analysis was conducted using the spectrophotometer Mansur method. The stock solution of the sunscreen formulation was prepared by ultrasonicate 1.0 g sample of sunscreen with 100 mL ethanol at 50% for 30 minutes. The stock solution was then filtered through Whatman No. 1 filter paper to remove insoluble particles. The filtrate serves as the stock solution for subsequent analysis. For UV-visible spectrophotometric analysis, the stock solution was subjected to two-step serial dilution. The first dilution yielded a 1:10 dilution, and the second dilution produced a 1:5 dilution. The absorbance of the second dilution was scanned across the wavelength range of 250-400 nm to determine the full UV absorption profile. All measurements were performed in triplicate to ensure reproducibility and accuracy. The SPF of the formulation was calculated using the Mansur equation:

$$SPF = CF \times \sum_{\lambda=290}^{320} EE(\lambda) \times Abs(\lambda) \quad (3)$$

where:

CF = correction factor (10)
EE(λ) = erythemal effect spectrum at wavelength λ
I(λ) = solar intensity spectrum at wavelength λ
Abs(λ) = measured absorbance of the sample at wavelength λ

Each absorbance value at the seven wavelengths was multiplied by its corresponding EE × I constant. The resulting products were summed and then multiplied by the correction factor (CF = 10) to obtain the SPF value of the formulation. Triplicate measurements were averaged, and the standard deviation was calculated to assess the precision of the analysis.

3.7 Statistical Analysis and Significance of Study

Statistical analysis was performed to evaluate the reliability, reproducibility, and significance of the experimental data acquired from extraction, biofunctional characterisation, and formulation studies. All experimental measurements were conducted in triplicate, and results were expressed as mean ± standard deviation to make the result consistent. In the process of formulation development, the Design of Experiments (DoE) tool has been

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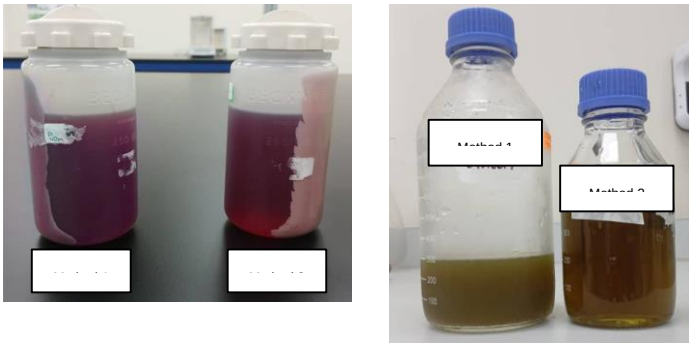
utilised to investigate the impact and interactions of critical formulation variables on physicochemical properties, biofunctionalities, and sun protection factor.

4. Result and Discussion

4.1 Visual and Physical Characteristics of Botanical Extracts Obtained Using Two Ultrasound-Assisted Extraction Methods

The effectiveness of the extraction methods was evaluated based on the visual appearance, clarity, and physical characteristics of *Rosa damascena* and *Camellia sinensis* extracts obtained using ultrasound-assisted aqueous extraction with *Moringa oleifera* coagulant (method 1) and ultrasound-assisted hydroethanolic extraction (method 2).

Figure 4.1 shows *Rosa damascena* and *Camellia sinensis* extracts from method 1 yield a darker-coloured, more turbid extract with visible sedimentation, whereas method 2 produced a lighter-coloured, clear extract. Indeed, the intense colouration and turbidity of method 1 could be due to the hydrophobic solvent systems along with the ultrasonication at high temperature (≈83 °C), which favoured the extraction of highly polar compounds, including anthocyanins, proteins, polysaccharides, and other water-soluble components of rose petals [8]. In contrast, method 2 employed 71% ethanol and water with lower ultrasonic conditions (75 °C temperature and 55% amplitude), which improved selective solvent extraction with respect to phenolics and flavonoids and minimised insoluble plant material [9]. This resulted in clarified and homogenous extracts being obtained from *Rosa damascena* and *Camellia sinensis.*



(a) **(b)**

Fig. 1 *Visual Comparison of Rosa damascena Extracts (a) and Camellia sinensis Extracts (b) Using Two Extraction Methods*

4.2 Comparative Analysis of Bioactive Content in Plant Extracts from Two Extraction Methods

Figure 2 indicates that the second extraction method achieved higher efficiency for both antioxidant and anti-inflammatory compounds in *Rosa damascena* and *Camellia sinensis* extracts. TAO (Total Antioxidant) refers to the potential extraction efficiency of antioxidant compounds determined via DPPH assay, while TAI (Total Anti-Inflammatory) represents the potential extraction efficiency of anti-inflammatory compounds determined via BSA denaturation assay. For antioxidant extraction efficiency, rose extract showed a higher extraction efficiency (2.77%) compared to the aqueous method (1.28%), while green tea extract showed a slightly higher extraction efficiency (2.14%) compared to 2.00%. Similarly, anti-inflammatory extraction efficiency showed a significantly higher percentage with the second method, with rose extract showing a substantially higher value (2.55%) compared to 0.27%, and green tea extract for the first method is 0.14% compared to 2.22% in the second method. The enhanced recovery in the second method can be attributed to ultrasonic cavitation, which disrupts cell walls and facilitates solvent penetration, and the use of hydroethanol, which combines the high polarity of water with the moderate polarity of ethanol [9]. This solvent system improves the solubility of intermediate-polarity phytochemicals, such as polyphenols, flavonoids, and phenolic acids, promoting higher recovery of both hydrophilic and moderately lipophilic bioactive compounds [9]. These results align with previous studies, demonstrating that the second extraction method is more effective, particularly for rose extract.

Hydroethanolic systems combine the high polarity of water with the moderate polarity of ethanol, enabling the extraction of a broader spectrum of bioactive compounds [9]. Many antioxidant and anti-inflammatory phytochemicals, including polyphenols, flavonoids, and phenolic acids, exhibit intermediate polarity and limited solubility in purely aqueous media [10]. The presence of ethanol reduces solvent polarity, thereby enhancing the solubility of these compounds and facilitating their diffusion from the plant matrix. As a result, hydroethanolic extraction promotes higher recovery of both hydrophilic and moderately lipophilic bioactive compounds [11].

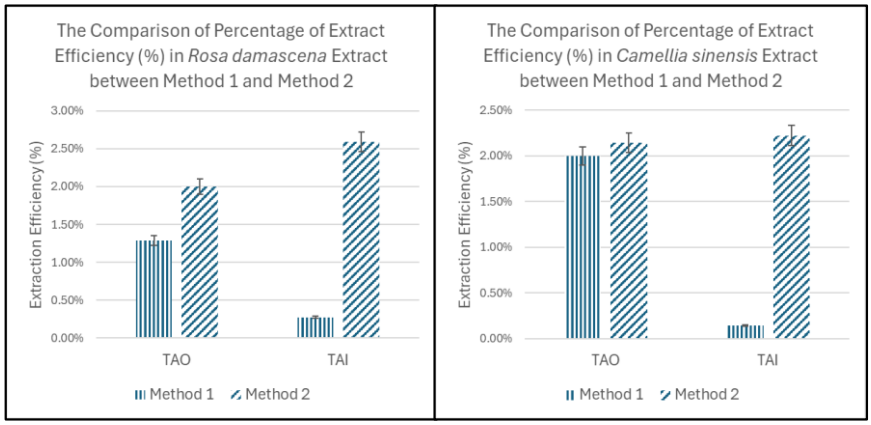


Fig. 2 *The Comparison of Percentage of Extract Efficiency (%) in Plant Extracts between Aqueous Extraction (Method 1) and Hydroethanolic Extraction (Method 2)*

4.3 Formulation of a Rose Water-Based Anti-Pollution Sunscreen and Makeup Setting Mist Analysis

4.3.1 Selection of Optimal Formulation Run Based on Texture Analysis

Figure 3 presents the visual texture evaluation of formulation runs R1-R9 based on their appearance, spreadability, and homogeneity when applied on glass slides. Formulation runs R1, R3, R4, R8, and R9 exhibited smooth and uniform textures with good homogeneity, indicating adequate structural integrity. However, R1, R3, and R4 were excessively viscous, limiting flow and spreadability and rendering them unsuitable for spray-based applications due to potential atomisation issues. In contrast, runs R2 and R6 showed excessive spreading and signs of low viscosity, suggesting weak internal structure and possible phase instability. Formulation runs R5 and R7 displayed intermediate behaviour, combining acceptable spreadability with maintained homogeneity. Based on these observations, runs R5–R9 were selected for further SPF analysis, as they demonstrated lower apparent viscosity, improved flow characteristics, and suitable physical properties for spray delivery, ensuring proper atomisation, uniform skin distribution, and reliable SPF evaluation.

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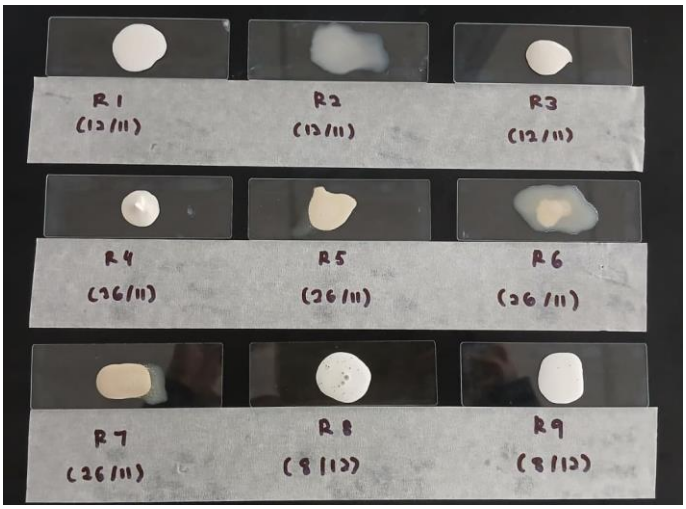

Fig. 2 *Visual texture evaluation of formulation runs (R1–R9)*

4.3.2 SPF Value Analysis Testing (Mansur Method)

Figure 4 visualised the data of SPF value between 5 formulation runs, R5 - R9. The data clearly shows a broad range of efficacy values. Run R9 had the highest mean value in terms of SPF; it was around 37, easily placing it in the high-range protection category. Thus, the formulation demonstrated higher in vitro photoprotective performance. Run R8 also shows a promising SPF value at SPF 31, which is also classified as high protection [12]. Mineral-based formulations containing zinc oxide have been reported to exhibit in vitro SPF values typically ranging between 20 and 50 depending on particle size, dispersion quality, and film uniformity [12]. The SPF values observed in this study fall within this reported range, suggesting that formulation stability and uniform UV filter distribution contributed to improved photoprotective performance. In contrast, R6 and R7 exhibited lower SPF values, indicating limited photoprotective potential, giving a very low mean SPF of about 7.5 and 3.2, respectively, indicating minimal sun protection. This might be due to clear signs of phase separation, non-homogeneity, and potential aggregation of solid material. This observation confirms that the failure to achieve effective SPF is a direct consequence of physicochemical instability, whereby the UV filters are no longer uniformly distributed within the emulsion base, preventing the formation of a continuous protective film when applied [13]. The SPF value calculated using Mansur spectrophotometric method represents in vitro screening estimates and cannot be used for commercial product labelling or regulatory claims without in vivo SPF testing in accordance with cosmetic regulatory guidelines.

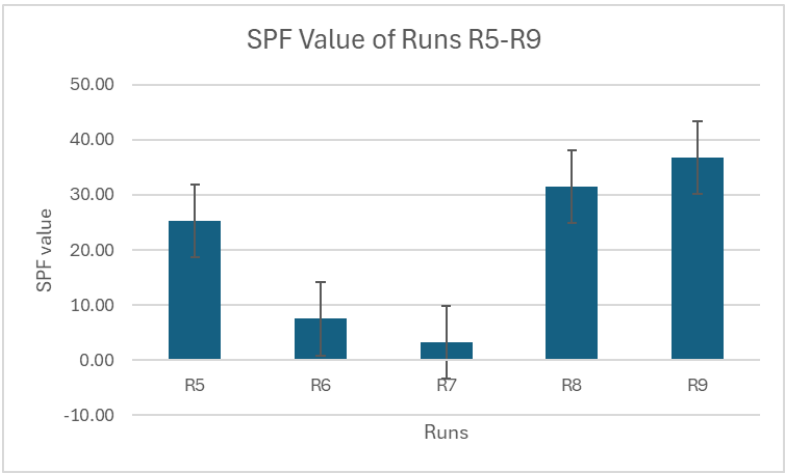

Fig. 4 *SPF Value Comparison of Formulation Runs (R5-R9)*

The superior antioxidant and anti-inflammatory extraction efficiencies achieved using the hydroethanolic method directly translated into enhanced photoprotective performance of the final formulations. Method 2 significantly increased the recovery of bioactive compounds from *Rosa damascena* and *Camellia sinensis*, with a particularly pronounced effect in rose extracts, attributable to improved solubilisation of moderately polar phytochemicals such as polyphenols and flavonoids. These compounds contribute to UV attenuation, radical scavenging, and inflammation mitigation. Accordingly, formulations incorporating these optimised extracts exhibited markedly higher SPF values, with R9 and R8 achieving high-protection levels (SPF ≈ 37 and 31), whereas unstable formulations (R6, R7) showed minimal SPF due to phase separation and non-uniform UV-filter distribution. These findings establish a direct link between extraction chemistry, bioactive availability, and formulation stability in governing photoprotective efficacy, underscoring the necessity of hydroethanolic extraction and physicochemical homogeneity for the development of multifunctional cosmetic systems.

5 Conclusion

This study developed a multifunctional rose water–based sunscreen and makeup setting mist incorporating botanical antioxidants and mineral UV filters. Ultrasound-assisted hydroethanolic extraction produced higher potential antioxidant and anti-inflammatory values compared to aqueous extraction using *Moringa oleifera* coagulant by producing clearer and more stable extracts, attributed to improved recovery of moderately polar phytochemicals such as polyphenols and flavonoids. The formulation optimisation method using Design of Experiments demonstrated that physicochemical stability and uniform mineral UV filter dispersion were critical for in vitro sun protection performance, with formulations R9 (≈37 SPF) and R8 (≈31 SPF) showing the best overall performance. The higher SPF values were associated with improved formulation stability and zinc oxide dispersion within the mist system, highlighting the role of formulation optimisation in influencing functional performance. Overall, the results indicate the potential of integrating photoprotection, antioxidant defence, anti-inflammatory activity, and cosmetic setting functionality into a single sprayable, clean-label, mineral-based formulation suitable for urban skincare applications.

5.1 Limitations

This study utilised in vitro assays to evaluate antioxidant activity, anti-inflammatory potential, and photoprotective performance. These assays provide preliminary screening data but do not account for skin penetration, residence time, real-world pollutant adhesion, or pollutant removal mechanisms. Further validation using ex vivo skin models or in vivo clinical studies are required to confirm practical efficacy. functionality into a single sprayable, clean-label, mineral-based formulation suitable for urban skincare applications.

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