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A Green Approach to Odour Control: Development of a Natural-Ingredient Deodorant Formulation Enriched with Plant-Based Bioactives

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Abstract

Conventional deodorant products commonly rely on synthetic antimicrobial agents and fragrance systems, raising concerns regarding skin compatibility, disruption of the axillary microbiome and environmental sustainability. This study aimed to develop and evaluate a natural-ingredient deodorant formulation enriched with plant-based bioactives as a green approach to underarm odour control. The scope of the research involved screening selected natural actives, namely magnesium hydroxide, zinc ricinoleate, kaffir lime essential oil, rose essential oil and tea tree essential oil, for their functional properties and incorporating the most effective bioactives into prototype deodorant formulations. Antimicrobial activity against *Staphylococcus sp.* was evaluated using agar diffusion assays, while antioxidant capacity was assessed using DPPH and FRAP methods. The formulated deodorants were further characterized in terms of pH, texture, spreadability and stability under selected storage conditions. The results demonstrated that the plant-based bioactives exhibited measurable antimicrobial activity with inhibition zones ranging 14.5 ± 0.29 to 28.3 ± 0.33 mm and antioxidant activity between 0.235 ± 0.001 and 0.269 ± 0.001 AU at 517 nm. The selected deodorant formulations showed skin-compatible pH values (7.5-9.4), acceptable physical stability and retention of functional properties. In conclusion, the findings support the feasibility of incorporating plant-based bioactives into natural deodorant formulations as a skin-friendly and sustainable odour control alternative.

1. Introduction

Underarm malodour results from the microbial degradation of sweat components on the skin surface and remains a common concern addressed through the use of deodorant products. However, increasing awareness of skin sensitivity, axillary microbiome disruption, and environmental sustainability has raised concerns regarding the safety and long-term suitability of many existing deodorant formulations [18]. Although a growing number of products are marketed as natural alternatives, some still contain ingredients such as baking soda, alcohol, or high concentrations of essential oils, which may cause irritation, pH imbalance, and inconsistent performance, particularly among individuals with sensitive skin [4]. Furthermore, many natural deodorant formulations lack systematic scientific validation and optimisation, leading to variability in functional efficacy and physicochemical stability [4]. Recent studies have highlighted the potential of plant-based functions while maintaining better skin compatibility [12]. Nevertheless, integrated investigations that combine bioactives screening, formulation development, and physicochemical evaluation of natural deodorant systems remain limited. Therefore, this study focuses on the development and evaluation of a natural-ingredient deodorant formulation enriched with selected plant-based bioactives as a scientifically supported and sustainable approach to odour control.

2. Methodology

2.1 Selection of Raw Materials

Raw materials were selected based on their functional relevance to deodorant formulation, skin compatibility and sustainability considerations. Mineral-based ingredients such as magnesium hydroxide and zinc ricinoleate were chosen for their odour-control and antimicrobial functions while plant-based bioactives were incorporated for their reported anti-inflammatory and antioxidant properties. All selected materials were suitable for topical application and were subjected to preliminary functional prior to formulation.

2.2 Screening of Bioactives Ingredients

The anti-inflammatory activity of selected bioactives samples was evaluated using the bovine serum albumin (BSA) protein denaturation assay, where samples were incubated with BSA solution under controlled conditions and the extent of protein denaturation was determined by measuring absorbance (660 nm) using a UV–Vis spectrophotometer. Total antioxidant activity was assessed using both the 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging assay (517 nm) and the Ferric Reducing Antioxidant Power (FRAP) assay (593 nm), in which the antioxidant capacity of the samples was quantified based on their ability to scavenge free radicals and reduce ferric ions, respectively, with absorbance readings recorded at the specified wavelengths. Antimicrobial activity was determined using the agar diffusion method against *Staphylococcus* sp., where prepared samples were applied onto inoculated agar plates and incubated to allow bacterial growth inhibition. The diameter of inhibition zones was measured to evaluate antimicrobial effectiveness. All assays were conducted in triplicate to ensure accuracy and reproducibility of the results.

2.3 Deodorant Formulation Development

Deodorant formulations were developed using a structured formulation strategy based on mixture design principles from Design of Experiment (DoE). The deodorant formulations were prepared by first accurately weighing all ingredients according to the predetermined formulation design. The oil phase, consisting of shea butter and capric triglyceride, was heated on a controlled hotplate at 60–70°C until completely melted and homogenous then added with beeswax. The mixture was then removed from direct heat and allowed to cool to 50–60°C, after which magnesium hydroxide, zinc ricinoleate and tapioca starch were gradually incorporated under continuous stirring to ensure uniform dispersion and prevent clumping. Upon further cooling to approximately 45°C, rose essential oil and kaffir lime essential oil were added, followed by vitamin E as a skin-soothing and antioxidant agent, with gentle mixing to maintain homogeneity. The molten deodorant was subsequently poured into polypropylene containers at around 45°C and allowed to cool and solidify at room temperature prior to further physicochemical, functional and stability evaluations.

2.4 Physicochemical Characterisation of Formulations

Physical characterisation of the deodorant formulations was conducted to evaluate their suitability for topical application. Visual appearance and colour were assessed through direct observation to identify any visible defects, phase separation or surface irregularities [11]. Odour evaluation was performed organoleptically to determine fragrance consistency and the presence of any rancid or off odours [15]. Texture and hardness were assessed manually by applying gentle pressure to determine smoothness, firmness or stickiness [10]. Spreadability was evaluated using the glass plate compression method, where a fixed amount of deodorant was placed between two glass plates and the spread diameter was measured under a standard load where measurements were conducted in triplicate and expressed as relative standard deviations (%RSD) to ensure reproducibility [2]. The pH of each formulation was determined by dispersing 1.0 g of deodorant in 10 mL of distilled water to obtain a homogeneous mixture, followed by measurement using a calibrated digital pH meter, with triplicate readings recorded to confirm accuracy. The acceptable pH range for skin application was considered based on the alkaline nature of magnesium hydroxide-containing deodorants, as reported in previous studies [17].

2.5 Stability Testing

Stability testing of the deodorant formulations was conducted to evaluate their physical and chemical stability under different storage conditions over a 14-day period. Three containers from the selected batch were prepared, labelled, and stored under refrigerated (4 °C), ambient (25 °C), and accelerated (40 °C) conditions, with observations recorded on Day 0, Day 7, and Day 14. Parameters assessed included visual appearance, colour, odour, texture, hardness, spreadability and pH. In addition, a heat stress test was performed to assess thermal stability, in which approximately 4 g of each formulation was placed in a clean crucible, loosely covered with aluminium foil, and exposed to 40 °C in a preheated oven for 4 hours, with temperature monitored at 1-hour intervals to prevent overheating [9]. After heat exposure, samples were cooled at room temperature and visually examined for signs of instability such as softening, sweating, oil separation, colour change, odour alteration or surface cracking which are commonly used indicators of thermal instability in semisolid cosmetic formulations [3].

2.6 Functional Evaluation of Selected Formulations

The total anti-inflammatory and antioxidant activities of the selected deodorant formulations were evaluated to determine the retention of functional properties in the final product. Analyses were conducted using the same reagents, assay procedures, and experimental conditions described previously for the anti-inflammatory (BSA protein denaturation) and antioxidant (DPPH and FRAP) assays in Sections 2.2, with modifications applied only to sample preparation to account for the deodorant matrix. An accurately weighed amount of deodorant sample was dissolved in an appropriate solvent to obtain a homogeneous dispersion prior to analysis. The prepared samples were then subjected to anti-inflammatory and antioxidant assays, and absorbance values were measured using a UV–Vis spectrophotometer at the respective wavelengths specified earlier. All measurements were performed in triplicate to ensure reliability and reproducibility of the results.

2.7 Data Analysis Strategy

This study applied a quantitative data analysis approach, where experimental results were expressed as mean ± standard error from triplicate measurements to enable objective evaluation and comparison of formulation performance. Limited qualitative observations on appearance, texture, and odour were used to support the interpretation of stability and product suitability.

3. Results and Discussion

3.1 Functional Screening of Raw Materials

3.1.1 Anti-inflammatory Activity of Raw Materials

The anti-inflammatory activity of selected deodorant raw materials was assessed using a protein denaturation inhibition assay at 0.2 mg/mL (Table 1). Plant-based essential oils demonstrated markedly higher inhibitory effects than mineral-based components. Kaffir lime essential oil exhibited the greatest activity (95.1%), followed by rose essential oil (94.7%) and tea tree essential oil (91.2%). In contrast, magnesium hydroxide and zinc ricinoleate showed lower inhibition values of 79.1% and 78.0%, respectively. Correspondingly, essential oils recorded lower absorbance values (0.039–0.072) compared with mineral ingredients (0.171–0.180), indicating greater protection against protein denaturation.

Table 1: Anti-inflammatory activity of selected raw materials by protein denaturation inhibition assay at 0.2 mg/mL (n=3)

Ingredient	Absorbance (660 nm) (Mean ±SE)	Protein Denaturation Inhibition (%)
Tea Tree Essential Oil	0.072 ± 0.002	91.2
Rose Essential Oil	0.043 ± 0.001	94.7
Kaffir Lime Essential Oil	0.039 ± 0.001	95.1
Magnesium Hydroxide	0.171 ± 0.003	79.1
Zinc Ricinoleate	0.180 ± 0.003	78.0

These findings highlight the superior anti-inflammatory potential of plant-derived bioactives relative to conventional deodorant actives. The high inhibition observed for essential oils is consistent with their known content of bioactives phytochemicals, including terpenes and phenolic compounds, which can stabilise proteins and suppress inflammatory processes [5]. In contrast, magnesium hydroxide and zinc ricinoleate primarily function through physicochemical mechanisms such as pH modulation and odour adsorption rather than direct biological activity [16].

Overall, the results support the incorporation of essential oil–based bioactives into deodorant formulations to enhance skin compatibility and provide added functional benefits beyond odour control. This reinforces their suitability for the development of natural, skin-friendly cosmetic products.

3.1.2 Antioxidant Activity of DPPH Assay

The antioxidant activity of the selected raw materials was evaluated using the DPPH radical scavenging assay at 0.5 mg/mL (Table 2). Magnesium hydroxide exhibited the highest scavenging activity (74.5%), followed by rose essential oil (72.7%), tea tree essential oil (71.7%), kaffir lime essential oil (71.0%), and zinc ricinoleate (70.9%). Correspondingly, magnesium hydroxide showed the lowest absorbance value (0.235 ± 0.001), indicating greater free radical neutralisation compared with the other materials.

Table 2: Antioxidant activity of raw materials by DPPH assay (0.5 mg/mL) (n=3)

Ingredient	Absorbance (517 nm) (Mean ± SE)	%Scavenging
Tea Tree Essential Oil	0.261 ± 0.002	71.7
Rose Essential Oil	0.252 ± 0.001	72.7
Kaffir Lime Essential Oil	0.268 ± 0.002	71.0
Magnesium Hydroxide	0.235 ± 0.001	74.5
Zinc Ricinoleate	0.269 ± 0.002	70.9

The relatively high DPPH scavenging observed for magnesium hydroxide may be attributed to its alkaline nature, which can influence radical stability under assay conditions. However, the essential oils also demonstrated appreciable antioxidant activity, reflecting the presence of bioactives phytochemicals such as terpenoids and phenolic compounds known for their radical-scavenging properties. Although zinc ricinoleate exhibited the lowest activity among the tested materials, its antioxidant performance remained comparable within the formulation context.

Overall, the results indicate that both mineral-based and plant-derived ingredients contribute to antioxidant capacity, with essential oils offering added biofunctional value relevant to skin protection and formulation stability. This supports their incorporation into natural deodorant systems where antioxidant activity is desirable alongside odour control and skin compatibility.

3.1.3 Antioxidant Activity by FRAP Assay

The antioxidant reducing capacity of the selected raw materials was evaluated using the FRAP assay at 1.0 mg/mL (Table 3). Among the tested samples, kaffir lime essential oil exhibited the highest FRAP value (0.247 mg/mL), followed by rose essential oil (0.237 mg/mL) and magnesium hydroxide (0.218 mg/mL). Tea tree essential oil and zinc ricinoleate showed comparatively lower reducing power, with FRAP values of 0.165 and 0.164 mg/mL, respectively. These trends were consistent with the corresponding absorbance values at 593 nm, reflecting differences in ferric ion (Fe^{3+}) reduction efficiency [7].

Table 3: Antioxidant activity of selected raw materials determined by FRAP assay at 1.0 mg/mL (n=3)

Ingredient	Absorbance (593 nm) (Mean ± SE)	FRAP Value (mg/mL)
Tea Tree Essential Oil	0.220 + 0.008	0.165
Rose Essential Oil	0.434 ± 0.011	0.237
Kaffir Lime Essential Oil	0.464 ± 0.013	0.247
Magnesium Hydroxide	0.378 ± 0.010	0.218
Zinc Ricinoleate	0.215 ± 0.007	0.164

The higher reducing capacity observed for kaffir lime and rose essential oils may be attributed to their richness in electron-donating phytochemicals, including phenolic compounds and oxygenated terpenes, which facilitate redox reactions. In contrast, the lower FRAP values for tea tree essential oil and zinc ricinoleate suggest weaker electron transfer capability at the tested concentration, potentially due to lower levels of redox-active functional groups or less favourable molecular structures for rapid electron donation. Magnesium hydroxide displayed moderate reducing power, indicating a limited but measurable contribution to antioxidant capacity.

Overall, the FRAP results support the role of plant-derived bioactives in enhancing the antioxidant profile of deodorant formulations. The superior reducing activity of selected essential oils reinforces their value as functional cosmetic ingredients capable of improving oxidative stability and contributing to skin-protective properties in natural deodorant systems.

3.1.4 Antimicrobial Activity

The antimicrobial activity of selected raw materials against *Staphylococcus aureus* was evaluated using an agar diffusion assay (Figure 1). The essential oils demonstrated stronger inhibitory effects than the mineral-based ingredients. Tea tree essential oil produced the largest inhibition zone, followed by rose essential oil and kaffir lime essential oil, indicating pronounced antibacterial activity. In contrast, magnesium hydroxide and zinc ricinoleate exhibited smaller inhibition zones, reflecting comparatively weaker antimicrobial performance under the test conditions.

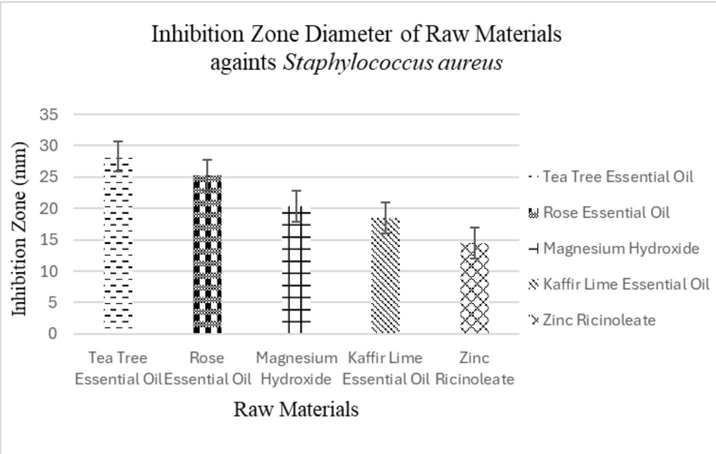

Fig. 1. Inhibition zone diameters of selected raw materials against *Staphylococcus aureus* (n=3)

The superior activity of the essential oils is consistent with their high content of bioactives phytochemicals, including terpenoids and phenolic compounds, which are known to disrupt microbial cell membranes and interfere with cellular metabolism [6]. Tea tree essential oil has been widely reported for its efficacy against Gram-positive bacteria such as *S. aureus*. The moderate inhibition observed for magnesium hydroxide and zinc ricinoleate is likely attributable to their indirect antimicrobial mechanisms, such as pH modification and odour-binding effects, rather than direct bactericidal action [1].

Overall, these findings highlight the effectiveness of plant-derived bioactives as antimicrobial agents in deodorant formulations. Their pronounced activity against *S. aureus,* a key contributor to axillary malodour, supports their incorporation as functional ingredients in natural deodorant systems, offering both odour control and enhanced skin compatibility.

3.2 Deodorant Formulation Development

Ten deodorant formulations (F1–F10) were developed using a mixture design based on Design of Experiment (DoE) principles to evaluate the effect of ingredient ratios on physical properties (Figure 2). All formulations produced semi-solid products with good homogeneity, smooth texture, and uniform appearance, with no visible phase separation or surface defects, indicating satisfactory formulation stability.

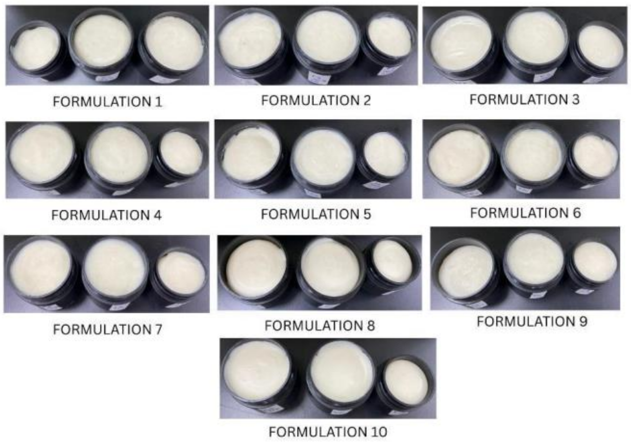

Fig.2. Physical appearance of deodorant formulations (F1-F10)

Minor variations in firmness and texture were observed among the formulations, which can be attributed to differences in wax-to-oil ratios within the formulation matrix. These results demonstrate that while all formulations achieved acceptable physical integrity, ingredient proportioning significantly influenced textural attributes. This highlights the importance of compositional optimisation in achieving desirable product performance and user acceptability in natural deodorant formulations [8].

3.3 Physicochemical Characterisation of Formulations

3.3.1 Visual Appearance, Texture, Hardness and Odour

All selected deodorant formulations exhibited a uniform visual appearance with no observable phase separation, indicating good physical integrity. Texture evaluation revealed smooth and homogeneous consistency across all samples, while hardness assessment demonstrated that the formulations were sufficiently firm to retain their shape yet adequately soft to allow ease of application. Organoleptic evaluation further confirmed that all formulations possessed consistent and acceptable odour characteristics.

Collectively, these findings indicate good compatibility among formulation components and satisfactory initial physical stability, both of which are essential for ensuring product performance and user acceptability.

3.3.2 Spreadability

The spreadability results of the deodorant formulations developed through the DoE approach are summarised in Table 4. The results show that all formulations exhibited spread diameters within an acceptable range for semi-solid deodorant products, indicating controlled and predictable spreading behaviour. Variations in spreadability were observed among formulations, which can be attributed to differences in wax-to-oil ratios, where higher wax content contributed to increased rigidity and slightly reduced spreading [2]. This trend demonstrates that formulation composition plays a key role in governing flow and deformation under applied load. Appropriate spreadability is important to ensure ease of application, uniform underarm coverage and user comfort, confirming that optimisation of wax and oil proportions is essential during formulation development [2].

Table 4: Spreadability results represented by average diameter and relative standard deviations, %RSD

Formulation No.	Average diameter (cm)	Relative Standard Deviation %RSD
1	2.15	9.87
2	2.10	6.73

3	2.15	9.87
4	2.10	6.73
5	2.20	19.29
6	2.10	6.73
7	2.15	3.29
8	2.05	3.45
9	2.30	18.45
10	2.05	3.45

3.3.3 pH Evaluation

The pH values of the deodorant formulations (Table 5) ranged from 7.53 to 9.33, reflecting an overall alkaline profile across the DoE-based formulations. The observed pH variability is primarily attributable to differences in magnesium hydroxide concentration, with additional contributions from interactions among other formulation components. Importantly, none of the formulations exhibited excessively high pH values, indicating that alkalinity was effectively controlled. This demonstrates that an appropriate balance was achieved between moderating alkalinity and preserving the functional role of magnesium hydroxide as an odour-neutralising agent within the formulation system [17].

Table 5: pH Readings for ten formulations of deodorant at room temperature (n=3)

Formulation No.	pH $\pm$ SE
1	8.10 $\pm$ 0.010
2	8.48 $\pm$ 0.014
3	8.37 $\pm$ 0.012
4	8.60 $\pm$ 0.016
5	8.37 $\pm$ 0.006
6	7.53 $\pm$ 0.013
7	7.55 $\pm$ 0.011
8	7.58 $\pm$ 0.012
9	8.31 $\pm$ 0.010
10	9.33 $\pm$ 0.018

3.4 Stability Assessment

The stability evaluation of the four selected formulations (F5, F7, F8, and F10) demonstrated satisfactory physical and chemical stability under room temperature, refrigerated (chiller), and incubated storage conditions over a 14-day period. Visual and olfactory assessments revealed no evidence of phase separation, colour change or abnormal odour at both Day 7 and Day 14, indicating good organoleptic stability.

Spreadability measurements remained consistent throughout the study, with low variability (%RSD = 0–7.07%), suggesting stable application properties across storage conditions, particularly under refrigerated storage.

Thermal stress testing at 40°C for 4h highlighted formulation-dependent differences in heat resistance. Formulation F5 exhibited the highest thermal stability, with no observable oil migration, followed by F10. In contrast, F7 displayed moderate instability, while F8 was the most heat-sensitive, showing visible oil pooling.

The pH values of all formulations showed minimal fluctuation between Day 7 and Day 14 and remained within an acceptable alkaline range (approximately pH 7.4–9.4), confirming chemical stability and continued suitability for topical application. Collectively, these results indicate that the selected formulations possessed satisfactory short-term stability, with F5 and F10 demonstrating superior overall performance under the tested conditions.

3.5 Functional Retention of Selected Deodorant

3.5.1 Antioxidant Activity by DPPH Assay

The DPPH scavenging activity graph in Figure 3 shows that all selected deodorant formulations (F5, F7, F8 and F10) exhibited measurable antioxidant activity at 1.0 mg/mL, indicating the successful retention of antioxidant properties after formulation. Among the formulations, F7 demonstrated the highest percentage of DPPH radical scavenging, followed by F5 and F8, while F10 showed comparatively lower activity.

This trend suggests that the formulation composition influenced antioxidant performance, likely due to differences in the concentration and interaction of plant-based bioactives within the semi-solid matrix [19]. The overall presence of antioxidant activity across all formulations confirms that the deodorant base did not significantly compromise the functional efficacy of the incorporated bioactives compounds.

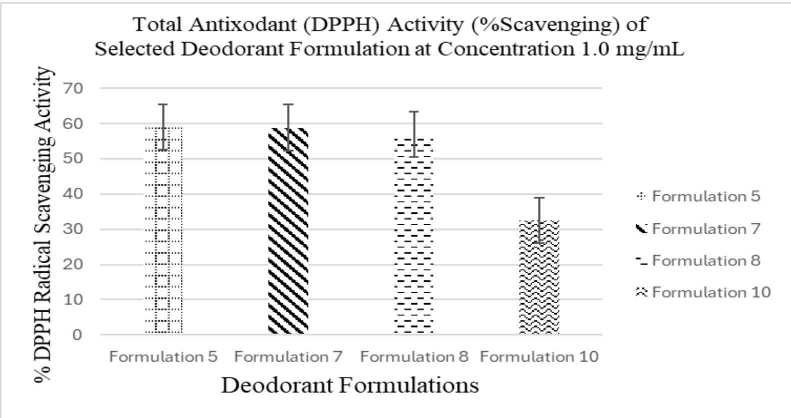

Fig.3. The percentage of scavenging of selected deodorant formulations at concentration 1.0 mg/mL (n=3)

3.5.2 Antioxidant Activity by FRAP Assay

Based on the FRAP graph in Figure 4, all four selected formulations exhibited ferric reducing antioxidant power, reflecting their ability to donate electrons and reduce ferric ions [7]. Formulation F7 recorded the highest FRAP value, indicating the strongest reducing capacity, followed by F5 and F8, while F10 showed the lowest FRAP activity.

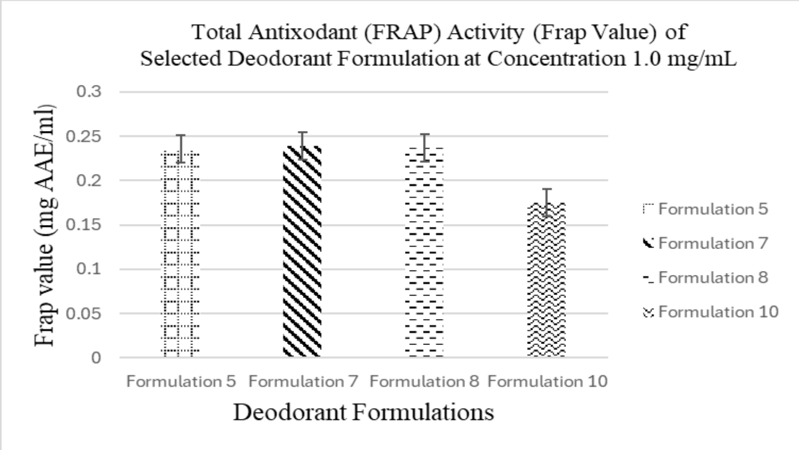

Fig.4. The FRAP value of selected deodorant formulations at concentration 1.0 mg/mL (n=3)

The observed trend is consistent with the DPPH results, suggesting that formulations with higher antioxidant activity possess more effective electron-donating compounds. These results demonstrate that the antioxidant potential of the plant-derived bioactives was preserved within the deodorant formulations, supporting their functional stability following formulation.

3.5.3 Anti-inflammatory Activity

The anti-inflammatory activity of the selected deodorant formulations (F5, F7, F8, and F10), evaluated using the BSA protein denaturation assay (Figure 5), demonstrated that all formulations could inhibit protein denaturation at a concentration of 1.0 mg/mL. Among the formulations, F7 exhibited the highest percentage inhibition, followed by F5 and F8, whereas F10 showed the lowest anti-inflammatory activity.

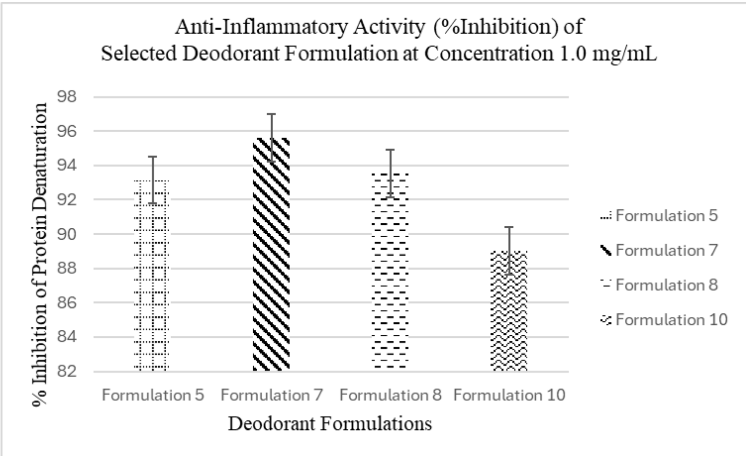

Fig.5. Percentage inhibition of protein denaturation by selected deodorant formulations (n=3)

These findings indicate that formulation composition significantly influenced anti-inflammatory performance, potentially due to synergistic interactions among the incorporated bioactives ingredients [13]. Importantly, the results confirm that the deodorant matrix preserved the anti-inflammatory functionality of the bioactives, supporting the suitability of the formulated products for reducing skin irritation associated with underarm application.

Collectively, the antimicrobial, antioxidant, and anti-inflammatory evaluations of both raw materials and formulated deodorants demonstrate that the selected bioactives system provides multifunctional performance relevant to underarm odour management and skin health. At the ingredient level, essential oils exhibited strong antimicrobial activity against *Staphylococcus aureus*, a key contributor to axillary malodour, while also showing substantial antioxidant and anti-inflammatory potential, supporting their role in suppressing odour-causing bacterial metabolism and mitigating irritation-related biochemical pathways. Mineral components such as magnesium hydroxide and zinc ricinoleate contributed complementary odour-control mechanisms through pH modulation and odour adsorption, albeit with comparatively lower biological activity.

Importantly, these functional attributes were retained following formulation, as the selected deodorant systems demonstrated measurable antioxidant capacity (DPPH and FRAP) and significant inhibition of protein denaturation, confirming preservation of bioactives efficacy within the semi-solid matrix. The combined bioactivities indicate a dual mechanism of action: direct suppression of odour-forming microorganisms alongside oxidative and inflammatory modulation that supports axillary skin barrier integrity. Together, these findings validate the formulation strategy as an integrated, skin-compatible deodorant platform that addresses both malodour generation and skin comfort, reinforcing its applied relevance for natural deodorant products designed to promote long-term axillary skin health.

Conclusion

This study demonstrated the feasibility of developing a natural deodorant incorporating plant-derived bioactives for effective underarm odour control. Functional screening identified kaffir lime and rose essential oils as strong anti-inflammatory agents, magnesium hydroxide as the most effective antioxidant component, and tea tree essential oil as the most potent antimicrobial. Ten formulations (F1–F10) were optimised using a Design of Experiments (DoE) approach and exhibited acceptable physicochemical properties, including uniform appearance, suitable texture, good spreadability, and skin-compatible pH (7.5–9.4). Stability testing of selected formulations (F5, F7, F8, and F10) confirmed the absence of phase separation, colour change, or odour degradation under varied storage conditions. Overall, the optimised formulation (F7) retained functional bioactivity with satisfactory stability, supporting the successful development of an effective, skin-compatible natural deodorant system.

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