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INCORPORATION OF BEESWAX OLEOGEL TECHNOLOGY IN MILLET COOKIES FOR FAT REDUCTION: A FUNCTIONAL AND NUTRITIONAL APPROACH FOR SUSTAINABILITY

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Abstract

Bakery products such as cookies are widely consumed but are often high in saturated fats due to the use of conventional solid fats, necessitating the development of healthier alternatives. The present study aimed to develop and evaluate beeswax-based oleogel as a fat replacer in millet cookies, with emphasis on formulation and textural characterisation. Oleogel was prepared using beeswax and sunflower oil in different ratios and evaluated through inversion test, microscopic analysis, and rancidity assessment. The oleogel formed a stable semi-solid system with a well- defined crystalline network and exhibited good oxidative stability up to 7 days, with slight deterioration observed on the 14th day. Cookies were prepared using buckwheat and foxtail millet flours at varying substitution levels along with a control sample. Sensory evaluation using a 9-point hedonic scale identified B1 (50% buckwheat flour + oleogel) and F1 (50% foxtail millet flour + oleogel) as the most acceptable formulations, with scores of 7.83 ± 0.75 and 7.50 ± 0.55, respectively. Physical analysis indicated improved spread (4.7 cm) and height (0.6 cm) in buckwheat-based cookies, while foxtail millet cookies exhibited reduced spread (4.5 cm) due to higher water absorption. Water absorption capacity increased from 5% in control to 10% and 15% in buckwheat and foxtail millet blends, respectively. Texture analysis showed increased hardness in oleogel-based cookies, with values of 42.17 N (B1) and 47.29 N (F1) compared to 23.9 N in control. Nutritional analysis revealed a significant reduction in fat and energy, along with improved protein content. The study concludes that beeswax-based oleogel can effectively replace conventional fat and, when combined with millet flours, can produce nutritionally improved cookies with acceptable textural and sensory properties.

Keywords: Beeswax oleogel, Fat replacer, Millet cookies, sustainability

Introduction

Cookies represent one of the most widely consumed bakery products worldwide due to their convenience, extended shelf life, and sensory acceptability. Nevertheless, conventional cookie formulations typically rely on solid fats such as butter, margarine, and shortening, which are rich in saturated fatty acids and may contain industrially produced trans fats. Excessive intake of these lipids has been consistently associated with an elevated risk of metabolic disorders, particularly cardiovascular diseases, thereby highlighting the need for reformulation strategies that reduce unhealthy fat content without compromising product quality (Das & Das, 2024; Givens, 2022).

In response to growing consumer demand for healthier bakery products, recent food science research has increasingly focused on the development of functional fat replacers capable of mimicking the structural and sensory roles of traditional fats while enhancing the nutritional profile of baked goods. Among these innovations, structured lipid systems such as oleogels have gained attention as promising alternatives due to their ability to modify lipid functionality and improve health-related attributes in bakery formulations (Manzoor et al., 2022).

Oleogels are structured lipid systems formed through the establishment of a three-dimensional crystalline network that entraps liquid oil, thereby imparting solid-like characteristics while largely preserving the original fatty acid composition of the oil phase (Abe et al., 2025; Tan, 2023). This structural modification enables oleogels to function as effective substitutes for conventional solid fats in bakery formulations, offering desirable textural and functional properties with improved nutritional potential. Among the diverse classes of oleogelators investigated, beeswax has attracted significant attention due to its natural origin, recognized food-grade safety, and strong capacity to form stable crystalline matrices exhibiting favourable thermal behaviour and mechanical strength (Pang et al., 2020; Abdolmaleki et al., 2022). Previous investigations have demonstrated that beeswax-based oleogels can be successfully incorporated into bakery and spreadable products, contributing to enhanced product stability, improved structural integrity, and a reduction in overall saturated fat content, thereby supporting their application as functional fat alternatives in healthier food design.

Previous investigations have demonstrated the successful incorporation of oleogel systems into lipid-based products such as margarine, spreads, and a variety of baked goods, highlighting their potential to partially or completely substitute conventional solid fats while preserving desirable technological and sensory attributes (Abdolmaleki et al., 2022; Le, 2025). These findings underscore the versatility of oleogel technology in enhancing the nutritional quality of processed foods without compromising structural integrity. Nevertheless, a substantial proportion of existing research has primarily focused on wheat-based formulations, with comparatively limited attention given to gluten-free matrices. In particular, there remains a notable research gap regarding the application and functional performance of oleogels in millet-based bakery products, which are increasingly recognized for their nutritional benefits and suitability for gluten-free dietary patterns.

Millets and pseudocereals, including buckwheat and foxtail millet, are gaining attention due to their superior nutritional profile, including high dietary fiber, protein, essential minerals, and bioactive compounds (Jose & Selvan, 2024; Hutabarat & Bowie, 2022). These grains also exhibit potential health benefits such as improved digestion, glycemic control, and antioxidant activity. Despite these advantages, the absence of gluten in millet flours presents significant challenges in dough formation and product texture, often resulting in inferior structural and sensory properties (Sharma et al., 2025; Singh & Sood, 2020).

In this context, the integration of beeswax-based oleogels into millet-based bakery systems offers a novel approach to overcome these limitations. The structural functionality of oleogels may compensate for the lack of gluten by improving dough consistency and enhancing textural attributes of the final product. However, limited studies have systematically evaluated the interaction between oleogels and millet flours and their combined effect on cookie quality.

Therefore, the present study aims to investigate the application of beeswax-based oleogel as a fat replacer in millet-based cookies and to evaluate its impact on physical, functional, and textural properties, thereby contributing to the development of healthier and innovative functional bakery products.

Methodology

Preparation of Beeswax-Based Oleogel

Beeswax-based oleogel was prepared using a thermal structuring method. Predetermined quantities of food-grade beeswax and sunflower oil were weighed according to the desired formulations and heated in a temperature-controlled water bath at **70–80 °C** under continuous stirring until complete dissolution of beeswax was achieved, resulting in a clear and homogeneous solution. The molten mixture was then transferred into clean, dry containers and allowed to cool undisturbed at ambient temperature to promote crystallization and formation of a stable semi-solid gel network.

Two experimental oleogel formulations were developed by varying the beeswax-to-oil ratios at 50:50 (O1) and 75:25 (O2) (w/w) to evaluate the influence of wax concentration on gel stability and functional properties. The prepared oleogels were stored at room temperature until further use in cookie formulation.

Characterization of Oleogel

Visual Appearance and Inversion Test

Oleogel stability was evaluated using a visual inspection and inversion method. Freshly prepared oleogel samples were transferred into glass test tubes and allowed to set undisturbed for **24 hours** at room temperature. The test tubes were subsequently inverted, and the absence of flow was considered indicative of stable gel formation.

Microscopic Examination

The microstructural characteristics of the oleogel samples were analyzed using polarized light microscopy. A small quantity of oleogel was placed on a glass slide and covered with a coverslip prior to observation. The crystalline structure and network formation were examined to assess the development of the oleogel matrix.

Preparation of Control Samples

Cookies were prepared using a standard creaming method with slight modifications. A control formulation was developed using refined wheat flour (maida) and butter as the conventional fat source. To choose the best suitable variation of oleogel, the 50 per cent of the fat in the cookie formula was replaced with two experimental variation of oelogel O1 and O2. The prepared cookies were subjected to sensory evaluation using 5 point hedonic scale to choose the better oelogel sample for the formulation of millet based cookies and taken as the control sample (C)

Selection of oelogel

Based on the results of above analysis, oleogel sample with better quality parameters similar to fat was chosen for the formulation of millet based cookies

Formulaiton of millet-based cookies

Experimental formulations based on millet with selected sample of oleogel were prepared by replacing butter with beeswax-based oleogel and incorporating millet flours, specifically buckwheat flour and foxtail millet flour, at substitution levels of 50%, 75%, and 100% in combination with refined wheat flour. The experimental variation made with buckwheat was named as BM1, BM2 and BM3 with wheat and buck wheat variation (w/w) in the ration of 50:50, 25:75, 0:100 respectively.

The experimental variation made with finger miller were named as FM1, FM2 and FM3 with wheat and finger millet variation (w/w) in the ration of 50:50, 25:75, 0:100 respectively. The prepared cookies were subjected to sensory analysis using 5 point hedonic scale.

Physical Analysis of Cookies

The prepared cookie samples were evaluated for selected physical characteristics to assess dimensional and structural changes during baking. The yield ratio, cookie dimensions, expandability were measured using standard laboratory procedures. Measurements were performed using calibrated weighing balances and digital vernier calipers, and values were recorded as mean measurements from replicate samples.

Determination of Water Absorption Capacity

Water absorption capacity of the flour samples was determined to evaluate hydration properties of millet and composite flours. The water absorption capacity influence the dough formation and dough extensibility.

Texture Profile Analysis

Textural properties of the cookie samples were determined using a texture analyzer to evaluate mechanical strength and structural integrity. Experimental cookie samples with millet and the control were subjected to a compression test, and parameters including hardness and brittleness were recorded based on the maximum force required to fracture the samples. Measurements were conducted under standardized test conditions to ensure reproducibility of results.

Nutrient analysis

The nutrient content of the best acceptable samples in two experimental variation were analysed and compared with the control cookies to analyse the reduction of fat and calorie content in the developed cookies.

Data Analysis

The experimental data were analysed using anova to study the interaction effects between oleogel concentration and quality parameters of the the millet cookies

Results and Discussion

The prepared oleogel exhibited a semi-solid, stable structure with no visible phase separation. During the inversion test, the sample did not flow or drip upon turning the container upside down, indicating effective immobilization of the liquid oil within the three-dimensional network formed by beeswax. The microscopic analysis of the beeswax–sunflower oil oleogel reveals the formation of a typical three-dimensional crystal network of beeswax-based oleogel, where darker wax structures trap lighter sunflower oil regions, indicating effective oil immobilization and strong binding capacity.

This confirms the effective gelation ability of beeswax, while also explaining the firm texture observed in oleogel-based cookies. Rancidity test revealed that prepared oleogel exhibited good oxidative stability during the initial storage period, with the onset of rancidity occurring only after extended storage**.**

The sensory evaluation results revealed that among the buckwheat millet flour-based cookies, sample BM1 (50% buckwheat flour + 50% maida with oleogel) obtained the highest mean score (7.83± 0.75), indicating better overall acceptability compared to BM2 (5.50 ± 0.55) and BM3 (3.50 ± 0.55). Similarly, among the foxtail millet flour-based cookies, sample FM1 (50% foxtail millet flour + 50% maida with oleogel) recorded the highest mean score (7.50 ± 0.55), showing superior sensory quality over FM2 (5.33 ± 0.82) and F3 (3.67 ± 0.52). A clear declining trend in sensory scores was observed with increasing levels of millet flour incorporation from 50% to 100%, suggesting that higher substitution levels negatively influenced key organoleptic attributes such as appearance, texture, flavour, aroma, and overall acceptability.

Although certain samples demonstrated slightly better consistency (lower standard deviation), their overall acceptability was comparatively low due to reduced mean scores. Therefore, greater emphasis was placed on mean sensory scores for selection, as they directly reflect consumer preference. Based on the highest mean scores along with acceptable levels of variation, samples BM1 and FM1 were identified as the most acceptable formulations. Hence, B1 (50% buckwheat flour + 50% maida with oleogel) and F1 (50% foxtail millet flour + 50% maida with oleogel) were selected and carried forward for further physicochemical and functional analysis.

The analysis of physical parameters of the selected cookie samples showed distinct variations between the control and oleogel-incorporated millet cookies. The total dough weight increased from control (100 g) to B1 (113 g) and F1 (128 g), primarily due to the higher quantity of milk incorporated in the millet-based formulations. After baking, a reduction in weight was observed in all samples, with final cookie weights of 95 g (control), 102 g (B1), and 115 g (F1). The percentage weight loss was relatively lower in the control (~5%) and higher in B1 (~9.7%) and F1 (~10.2%), which can be attributed to longer baking time (30 minutes) and higher moisture content in the oleogel-based samples, resulting in greater moisture evaporation.

The height of the dough was uniform (0.4 cm) across all samples, indicating consistency in dough preparation. After baking, an increase in height was observed, with B1 showing the highest thickness (0.6 cm), followed by control and F1 (0.5 cm). This suggests that B1 exhibited better structural development and aeration, possibly due to the balanced combination of buckwheat flour, maida, and oleogel.

The diameter of the dough remained constant (4.5 cm) for all samples prior to baking. Post- baking, a slight increase in diameter was observed in control (4.6 cm) and BM1 (4.7 cm), indicating normal spread during baking, whereas FM1 showed no change (4.5 cm), suggesting restricted spread which may be due to the higher fibre content and weaker gluten network in foxtail millet flour.

The number of cookies produced increased with dough weight, with F1 yielding the highest number (8 cookies), followed by BM1 (7 cookies) and control (6 cookies). Overall, the incorporation of oleogel and millet flours influenced the physical characteristics of cookies, with BM1 demonstrating better spread and height, while FM1 showed higher yield and moisture retention. These results indicate that oleogel-based millet cookies possess acceptable and comparable physical properties to the control sample.

The texture analysis graph of the control cookie shows a peak force of approximately 23.94 N, followed by a clear drop in the curve. This indicates that the cookie fractured easily under applied force, which is a typical characteristic of a crisp and well-structured cookie. The relatively low hardness value suggests that the cookie has a tender texture and good bite quality. This value falls within the desirable hardness range generally observed in standard cookies.

The texture graph for this sample BM1 shows a peak force of approximately 42.17 N, which is significantly higher than the control cookie. The curve shows a fracture after reaching the peak, indicating that the cookie still possesses a brittle structure. However, the higher hardness value suggests that the cookie is firmer and harder compared to the control. This may be due to the presence of buckwheat flour and the structuring effect of oleogel, which can increase the rigidity of the cookie matrix. However, it still falls within an acceptable range for crisp-type cookies, suggesting moderate consumer acceptability with scope for improvement.

The texture analysis of sample FM1 shows a maximum force of approximately 47.29 N, indicating the highest hardness among the tested samples. The curve gradually increases without a sharp drop immediately after the peak, suggesting that the cookie has a denser and more compact structure with reduced brittleness. The higher hardness may be attributed to the higher fiber content and water absorption capacity of foxtail millet flour, which can result in a firmer and less crisp cookie texture.Therefore, among the oleogel-based variations, the buckwheat cookie demonstrated a better balance between hardness and brittleness compared to the foxtail millet cookie**.**

Nutrient analysis showed the approximate reduction of 35-45% of fat content and corresponding reduction of in calorie density.

Sample BM1 recorded lower fat contents approximate reduction of 35– 45%. Similarly, the energy values decreased to 421 kcal (B1) and 366 kcal (B3), indicating a clear reduction in caloric density. Importantly, beyond the reduction in total fat, the quality of fat is significantly improved in oleogel-based cookies. The replacement of butter with sunflower oil structured in the form of oleogel introduces a higher proportion of unsaturated fatty acids, which are considered beneficial for cardiovascular health, unlike the saturated fats predominant in conventional cookies. Moreover, beeswax, being non-digestible, does not contribute to caloric value, further supporting the reduction in effective energy intake.

Conclusion

Overall, the combined effect of fat replacement using beeswax-based oleogel and the inclusion of nutrient-rich millet flours results in cookies with lower fat and energy content, improved protein levels, and better fat quality. These findings strongly support the potential of oleogel-based millet cookies as a nutritionally improved and healthier alternative to traditional butter-based cookies, without compromising their functional and compositional characteristics.

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