Development of Beewax Oleogels for Application in Food Sector

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Abstract—**The study explores the development and optimization of beeswax-based oleogels using sunflower oil and psyllium husk as components to create a functional fat substitute with improved nutritional and structural properties. Oleogels were formulated by structuring sunflower oil with beeswax and psyllium husk, following a response surface methodology design. Oil Binding Capacity and Free Fatty Acid values were the primary responses evaluated. The results demonstrated that OBC increased with higher beeswax and psyllium content, whereas higher sunflower oil content led to increased FFA values, indicating susceptibility to degradation. The optimized formulation was obtained and a desirable balance was achieved with OBC and FFA. The synergistic interaction between beeswax and psyllium enhanced the structural integrity of the oleogels, while sunflower oil provided a healthier fat base. Validation was done to confirm the reliability of the predictive model. The study confirms the potential of beeswax oleogels as viable fat replacers in food systems, especially in bakery applications, supporting health-focused innovation without compromising product quality.**

Index Terms—**Beewax oleogel, Oil binding capacity, Free fatty acid.**

I. Introduction

Beeswax oleogels are semi-solid systems formed when liquid vegetable oils are structured into a gel-like network using beeswax—an abundant lipid-based gelator consisting of esters, fatty acids/alcohols, and hydrocarbons. Unlike fully hydrogenated fats, gelation through beeswax preserves the nutritional integrity of unsaturated oils (usually > 90% of the oleogel). Beeswax is widely used as a gelator due to its strong structuring ability, food-grade status, and natural origin. When mixed with vegetable oils, beeswax forms a thermo reversible network capable of mimicking the texture and functionality of solid fats. Researchers have demonstrated that beeswax-based oleogels can be incorporated into bakery products, with cakes made using beeswax oleogels showing comparable crumb structure and softness to those prepared with traditional shortening. Importantly, beeswax oleogels reduce saturated and trans-fat content in the final product, addressing health concerns without sacrificing sensory quality [3].

[2] showed that waxes exhibit a variety of physicochemical properties given that they are made up of complex combinations such as hydrocarbons, fatty acids, fatty alcohols, and wax esters. The use of structuring techniques in liquid edible oils makes it possible to obtain semi-solid systems (oleogels), which can retain a solid consistency without adding solid fats, which are triglycerides with saturated or trans-isomeric acids. [4] explained about the various studies conducted on the ability of beeswax to structure only certain liquid vegetable oils. Waxes, particularly beeswax, are among the most common structure-forming agents for the production of oleogels. Beeswax has a complex mixture that can include various components. The early development of beeswax oleogels centered on defining optimal beeswax concentrations (typically 3–15% by weight) and sourcing techniques to create stable, crystalline networks. These structures typically form needle-like crystals that trap oil, imparting solid-like texture until thermal melting – a property critical for structuring applications.

Although oleogels are already utilized in medications and cosmetics, the food industry has not made extensive use of them. Wax-based oleogels are thermo-reversible gels that can be shaped to have the desired shape and qualities and heated and chilled without compromising the oleogelator effectiveness. In bakery and confectionary, substituting margarine/shortening with beeswax oleogels (using oils like corn, sunflower, high-oleic soybean) show that up to 75% fat replacement can maintain desirable texture, color, and spread, with consumer acceptability matching conventional products. Rheological properties like dough firmness—remain comparable in biscuits and cookies. Beeswax rice bran oleogels used in cake systems produced stable crystalline networks with melting points up to 66 °C. These gels delivered enhanced firmness, moisture retention, and bake-stable crumb structure.

II. Materials And Methods

The oleogels were prepared following the method prescribed by [8] with slight modifications. The sunflower oil is heated 80°C on a magnetic stirrer followed by addition of beewax and psyllium husk. The mixture is then cooled and furthur stored at 4°C. The experimental design matrix was suggested by the Design Expert (v.13.0.5.0) using Mixture Optimal of Response Surface Methodology (RSM). The suggested matrix consisted of 16 runs with different combinations for preparation of beewax oleogel and stearic acid oleogel. The responses were Oil binding Capacity (OBC) and Free Fatty Acid (FFA) value for both the oleogels prepared.

The independent parameters:

- Level of Beewax (6 – 10 %)
- Level of Psyllium husk (2 – 5 %)

- Level of Sunflower Oil (85 – 92 %)

The dependent parameters:

- Oil Binding Capacity (%)
- Free Fatty acid (%)

1.Oil Binding Capacity

The oil binding capacity was determined using centrifugation [1][4]. The samples were weighed and stored in refrigerator for 24h, after which they were centrifuged at 10000 rpm for 15 min at 20°C [11]. The oil which gets separated at top will be removed. The calculation is

$$\% \text{ Oil released} = \frac{(m1-m)-(m2-m)}{(m1-m)} \quad (1)$$

$$\text{OBC\%} = 100 - \text{Oil released} \quad (2)$$

Where,

m1 = weight of tube before centrifugation

m2 = weight of tube after centrifugation

m = weight of empty tube

2. Free Fatty Acid

The total titratable acidity was determined according to the AOAC method. Approximately 2.0 g of sample was used, dissolved in 25 mL of ether-alcohol solution (2:1) and add two drops of 1 % phenolphthalein indicator in ethanol. Titration was performed using 0.1 M sodium hydroxide solution in deionized water until the appearance of pink color, with a minimum persistence of 30 s [7]. The FFA content was calculated as

$$\% \text{ FFA} = \frac{V \times M \times 28.2}{m} \quad (3)$$

Where,
V = volume of solvent used
M = Molarity of the NaOH solution
m = Mass of the sample

III. Results And Discussion

The following table illustrates the design given by mixture RSM using Design Expert software where A: Psyllium Husk (%); B: Beewax (%); C: Sunflower Oil (%)

Table 1 Components and responses for beewax oleogel

Run Number	Components			Responses	
	A	B	C	FFA	OBC
1	2.52	6.00	91.47	1.123	51.93
2	3.03	10.00	86.97	2.355	69.26
3	5.00	7.62	87.38	1.452	59.46
4	5.00	9.52	85.48	1.883	68.03
5	3.80	6.00	90.20	1.175	45.55
6	3.03	10.00	86.97	2.326	73.07
7	3.75	7.83	88.42	1.561	64.60
8	2.49	7.16	90.35	1.418	65.72
9	3.75	7.83	88.42	1.784	67.76
10	5.00	9.52	85.48	1.946	66.68
11	3.75	7.83	88.42	1.552	61.11
12	5.00	6.00	89.00	1.148	50.17
13	4.29	8.92	86.79	1.778	61.58

14	2.00	9.74	88.26	2.038	68.74
15	2.52	6.00	91.47	1.153	55.99
16	2.00	8.46	89.54	1.746	66.99

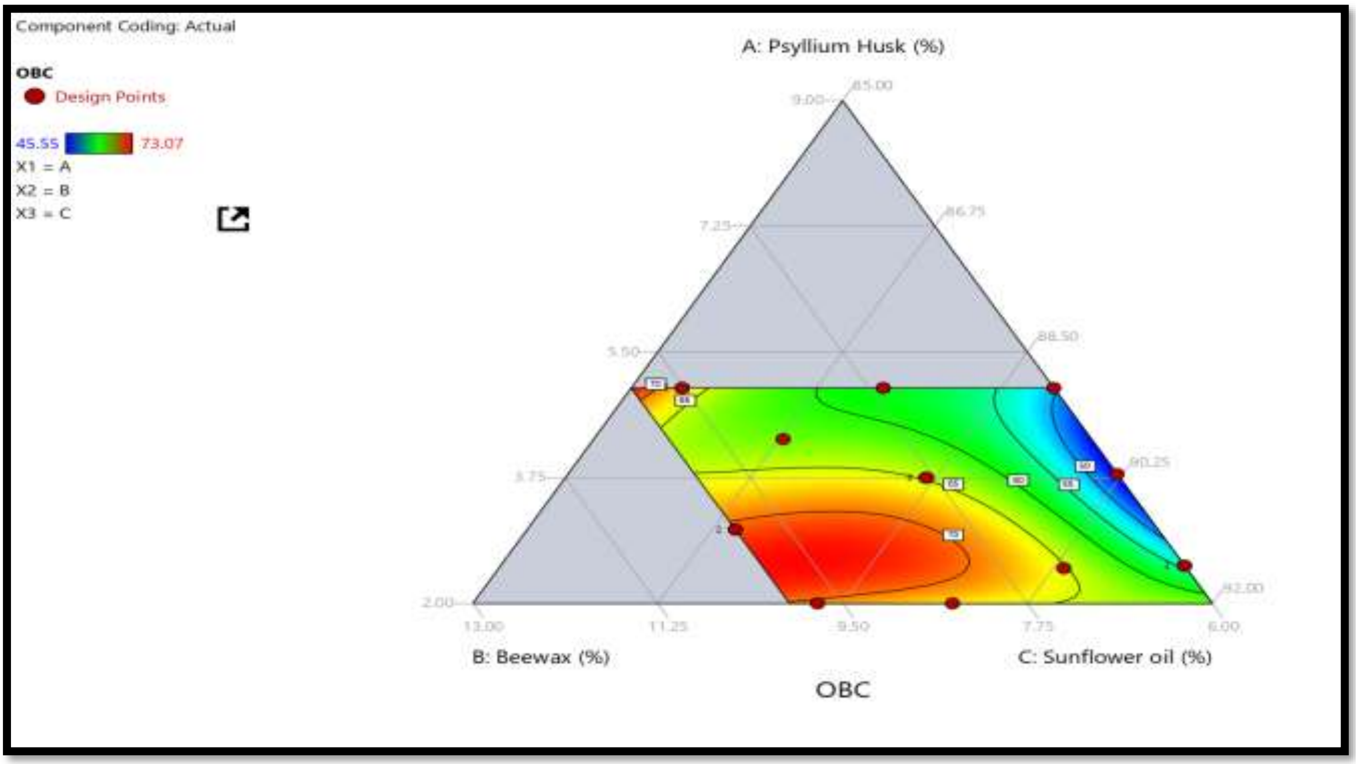

Figure 1 Contour graph for OBC of beewax oleogel

The figure 1 indicates that each side of the triangle represent one of the three components: A: Psyllium Husk (%) on the top corner, B: Beewax (%) on the bottom-left axis and C: Sunflower Oil (%) on the bottom-right axis. Also, every point inside the triangle represent a unique combination of A, B, and C that adds up to 100%.

The colored contours show the predicted OBC response across the composition space where blue (45.55%) represent lower OBC and green-yellow-red (73.07%) represent higher OBC. Contour lines within the triangle connect points of equal OBC. The gradient provides insight into how changing component ratios impacts OBC. The maximum value of OBC is on compositions in the red and yellow zone which represent moderate psyllium husk, high beewax, and low sunflower oil.

The curves labelled with numbers (e.g., 55, 60, 65) represent levels of equal OBC and explain how moving from blue to red crosses higher OBC regions. These help to visualise and interpret various trends on how the OBC values vary on different concentrations of beewax, psyllium husk and sunflower oil.

[10] mentioned that the value of OBC increases as the oleogelator value increases and maximum value can be observed when the concentration of oleogelator is maximum. From the table, we can see that for the run 1, 5, 12 and 15 the concentration of beewax was 6.00% and hence the OBC values obtained where the lowest. Similarly, for run 2 and 6 the concentration of beewax was 10.00% and the highest values of OBC was recorded for these runs. The obtained results are in accordance with the described study. Also, in this study beewax is the major contributor to OBC compared to psyllium husk but the use of psyllium husk was able to enhance the action of beewax to attained maximum OBC. The table shows that for the same concentration of beewax used, the values of OBC showed slight increase when the concentration of psyllium husk was increased. This can be explained as psyllium husk has good gelling properties and can create good oil fibre gels which contributed to the increased value of OBC [5]. Sunflower oil is the major component in the oleogel. It is observed increasing the oil content decreases the OBC values. This might be due to the dilution of beewax and psyllium husk components which could lead to weaker gels and hence the separation of oil would be more thus affecting negatively towards OBC.

The OBC increased with increasing beewax and psyllium husk content, indicating a synergistic effect oleogel and is also a complex function of its composition. Beeswax concentration is a major determinant due to its structuring properties [9], with higher concentrations leading to increased OBC. Psyllium husk contributes to this effect, often amplifying the impact of beeswax. Sunflower oil acts in concert with these components to establish the final oil-binding properties of the oleogel.

Each side of the triangle from the figure 2 represents one of the three components: A: Psyllium Husk (%) on the top corner, B: Beewax (%) on the bottom-left axis and C: Sunflower Oil (%) on the bottom-right axis. Also, every point inside the triangle represents a unique combination of A, B, and C that adds up to 100%.

The colored contours show the predicted FFA response across the composition space where blue (1.123%) represent lower FFA and green-yellow-red (2.355%) represent higher FFA. To maximize FFA, the focus should be on compositions in the red and yellow zone which represent moderate psyllium husk, high beewax, and low sunflower oil.

Thus, it can be concluded that sunflower oil is the major component that increases the value of FFA. This can be due to more sunflower oil make it more available to degradation or hydrolysis whereas when beewax and psyllium husk are present they act as a stabilizer to control the increase in FFA values. It was observed that as the amount of Sunflower Oil increases, the FFA values also rise dramatically. This is evident from the upward slope and red/orange coloration at high C values. Similarly, the lowest FFA values (blue zone) were seen where Beeswax was higher and Sunflower Oil was lower. Although, A is not directly shown on the front plane (since this is a 3D slice), the surface shape suggests minor variation in FFA along that direction. Psyllium husk may slightly lower FFA due to its moisture-binding or antioxidant properties but is not the dominant factor in this response.

[6] in their study has shown that oil degradation decreases as the amount of oleogelator like beewax increases and the degradation value of oil will always be higher compared to oleogels prepared from the same oil. Also, this study explains that degradability of oils is higher when they are measured immediately after preparation and a gradual decrease can be observed compared to initial values as for the preparation high temperature is used for long time.

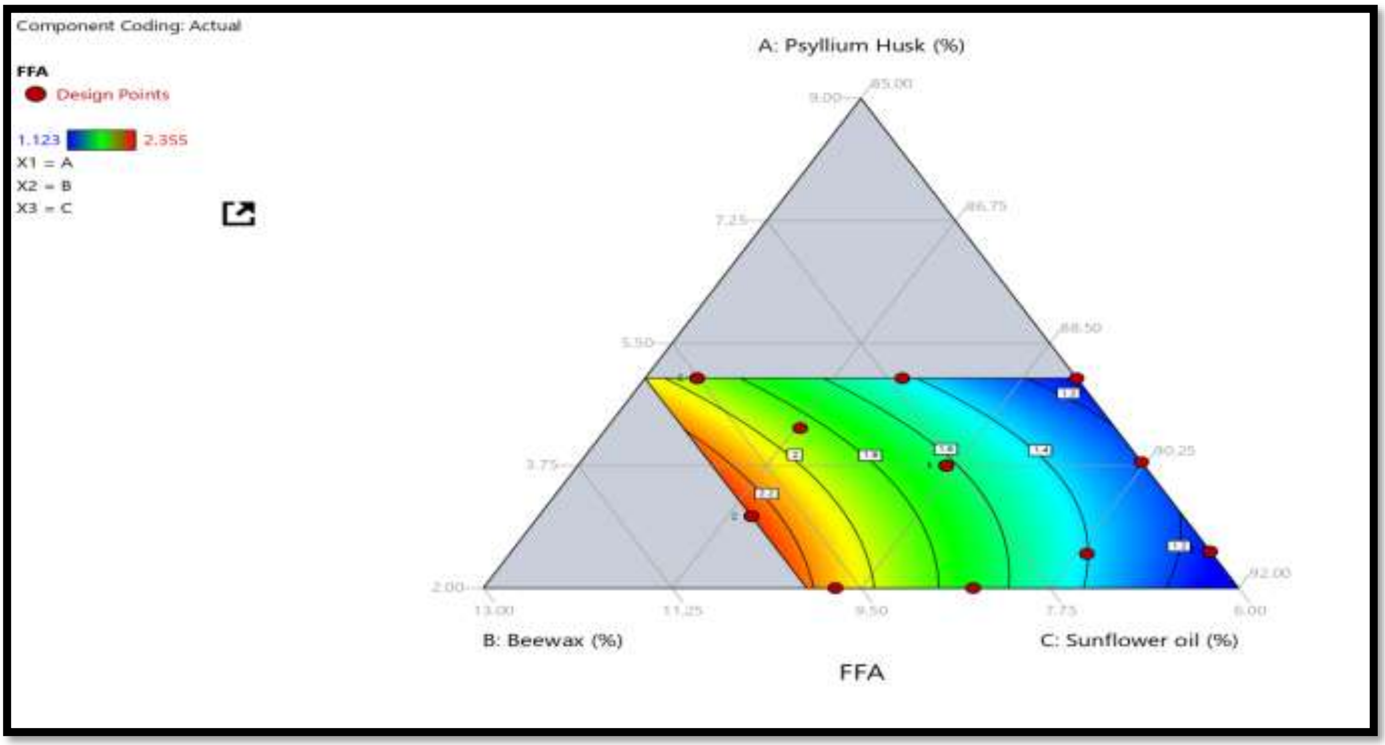

Figure 2 Contour graph of beewax oleogel for FFA

IV. Optimization of Process Parameters Using RSM

The optimization of process parameters was done to find the optimal combination of variables for making beewax oleogel with psyllium husk (A), beewax (B) and sunflower oil (C) that will give a result with maximum OBC and minimum FFA. The data received was processed using the design expert software. Using the parameters and their limits, the RSM recommended an optimized solution as shown in table 2 The mixture components were 8.44% beewax, 2.67% psyllium husk and 88.88% sunflower oil and responses were 71.60% for OBC and 1.7754 % for FFA. The overall acceptability of the model was 84% desirable.

The validation of beewax oleogel was done and the model is found to be acceptable. It indicates the actual values for FFA and OBC closely align with the predicted values and remaining well within their respective 95% prediction intervals.

Table 2 Optimized parameters for beewax oleogel

Optimized Factors			Optimized Responses		Desirability of the model
Beewax (%)	Psyllium Husk (%)	Sunflower Oil (%)	OBC	FFA	
8.44	2.67	88.88	71.60	1.7754	0.843

V. Conclusion

Beeswax oleogels represent a promising frontier in food-grade fat structuring: bridging the gap between nutrition and performance. Their structural adaptability, sensory equivalence to traditional fats, and customizable functionality make them suitable for baked goods, spreads, dairy analogues, and meat products. With increasing regulatory encouragement and evolving consumer preferences, beeswax oleogels are not only scientifically compelling but culturally on-trend—offering healthier, sustainable, and versatile solutions in modern food development. The development of beeswax oleogels offers a promising strategy to create healthier fat alternatives in food systems, particularly for applications like baked goods. The use of natural oleogelators such as beeswax and psyllium husk allowed effective structuring of liquid sunflower oil, achieving solid-like properties necessary for fat replacement. Experimental results showed that oil binding capacity was significantly influenced by beeswax concentration, with psyllium husk enhancing the gel matrix and stability. In contrast, sunflower oil content had an inverse effect on oil retention and increased susceptibility to free fatty acid formation. Through RSM optimization, the most desirable formulation—8.44% beeswax, 2.67% psyllium husk, and 88.88% sunflower oil—achieved high OBC (71.60%) and relatively low FFA (1.7754%), supporting both performance and nutritional objectives. The close agreement between predicted and actual values validated the model's reliability. These findings highlight the potential of beeswax oleogels as functional and sustainable alternatives to traditional solid fats. With increasing demand for health-oriented food innovations, beeswax oleogels offer a clean-label, natural solution for reducing saturated and trans-fat content while maintaining desirable texture and sensory properties in final products.

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