Journal of Applied and Natural Science
16(2), 526 - 533 (2024)
ISSN : 0974-9411 (Print), 2231-5209 (Online)
journals.ansfoundation.org

Research Article

Influence of frying conditions on colour kinetics and viscosity of frying medium employed for making Indian recipe *Gulabjamun*

Mukul Sain
Dairy Engineering Division, National Dairy Research Institute, Karnal-132001 (Haryana), India
P.S. Minz
Dairy Engineering Division, National Dairy Research Institute, Karnal-132001 (Haryana), India
Arijit Ray
Dairy Engineering Division, National Dairy Research Institute, Karnal-132001 (Haryana), India
Ankit Bihola
Dairy Technology Division, National Dairy Research Institute, Karnal-132001 (Haryana), India
Shaikh Adil*
Dairy Technology Department, Parul Institute of Technology, Parul University, Vadodara-391760 (Gujarat), India

*Corresponding author : E-mail: shaikh.adil23773@paruluniversity.ac.in

Article Info
https://doi.org/10.31018/jans.v16i2.5444
Received: February 3, 2024
Revised: April 6, 2024
Accepted: April 12, 2024

How to Cite
Sain, M. *et al.* (2024). Influence of frying conditions on colour kinetics and viscosity of frying medium employed for making Indian recipe *Gulabjamun*. *Journal of Applied and Natural Science*, 16(2), 526 - 533. https://doi.org/10.31018/jans.v16i2.5444

Abstract
Frying *Gulabjamun* in *Ghee* is key to its distinct taste and texture, but reheating frequency and conditions can affect the sweet's colour and consistency. It is important to understand this dynamic to ensure the desired quality of the final product. Based on the facts as mentioned above, the present study was conducted to analyse the change in colour and viscosity occurring in the *Ghee* during repetitive frying to cook *Gulabjamuns.*The change in colour attributes and viscosity of *Ghee* was monitored at various hours of frying. The results revealed that the *Ghee* became darker, the green hues became more prominent, and the yellow hues became more intense the longer it was fried. Besides, the most significant color change occurred during the 60-hour frying duration, as indicated by a decrease in lightness (L* value from 43.07 to 41.1) and a noticeable shift towards greener hues (Δa* value of -7.22334), suggesting that extended frying times lead to the darker and greener side. It attained its maximum viscosity after 12 hours of frying, with a shear stress of 19.10 Pa and viscosity of 0.66 Pa-s, which was correlated with the formation of a scum and the disappearance of steam bubbles. The physicochemical changes taking place in *Ghee* during the frying of *Gulabjamun* after repeated heating provide understanding to sweet makers for the selection of the appropriate frying medium and frying techniques, which ultimately assist in the improvement of the overall sensory attributes of the *Gulabjamun*.

Keywords: Colour, Frying, *Ghee*, *Gulabjamun,* Indian recipe, Viscosity

INTRODUCTION

India is the world's largest producer of milk (NDDB, 2023), with an extensive and diverse dairy industry (Sain *et al.,* 2020). Due to the importance of dairy products in Indian nutrition and the extensive participation of rural households in milk production, India's milk production has consistently increased over the years (Sain, 2019). *Gulabjamun* has become a popular Indian sweet prepared by mixing khoa, wheat flour (Maida), and baking powder. The Dhap variety of khoa, the leading dairy component in *Gulabjamun*, profoundly impacts its chemical and sensory characteristics. However, because of its short lifespan and periodic lack of availability, attempts have been made to find an alternative for khoa in the production of *Gulabjamun* (Kushwaha *et al.,* 2017).

Frying is a conventional technique that imparts desirable flavour, body, texture, and appearance to different foods. *Gulabjamun* is a traditional sweetmeat consisting of soft, syrup-soaked dough balls fried to a rich golden colour (Sharnabasava *et al.,* 2018). When dough balls are subjected to frying in hot *Ghee*, a series of chemical interactions occur between the *Ghee* and the various constituents present in the *Gulabjamun* (Kumar *et al.,* 2022b). The frying conditions and frequency of re-heating of *Ghee* influenced its properties, such as colour and viscosity, and also the resultant product (i.e., *Gulabjamun),* due to various heat reactions taking place during heating such as maillard browning, polymerization, formation of peroxide and hydroperoxides, etc. (Kumar *et al.,* 2022a).

The present investigation aimed to examine i) the selected physicochemical (colour and viscosity) changes that occur during the frying of the Indian recipe *Gulabjamun* in *Ghee*, ii) how the type of frying medium used, the frying temperature, and the frequency of re-heating influence the characteristics of the frying medium, iii) It is important to consider how changes frying medium, like oxidation and the breakdown of molecules, can affect the quality of fried food and health of the consumer.

MATERIALS AND METHODS

Preparation of *Gulabjamun*

The procedure for preparing *Gulabjamun* is shown in Fig. 1. 500g of *Gulabjamun* mix powder was taken and placed in a mixing bowl. A measured quantity of water (250–300 ml) was added to the mix and kneaded until a smooth dough was formed. Too much water resulted in a loose dough, while too little water led to a hard dough that was challenging to shape. Stiff dough produced irregularly fried *Gulabjamun* balls. The mixing bowl was covered with a wet muslin cloth to retain moisture, and the dough was allowed to rest for 10 minutes. From the dough, 15 g portions were accurately weighed and manually rolled into smooth, crack-free balls. Similar procedure was adopted by Mourya and Thakur (2021) to prepare and analyse sugar-free *Gulabjamun* made with skim milk powder. Table 1 details how the *Gulabjamun* mix (developed at ICAR-NDRI, Karnal) was prepared, including the use of roller-dried skimmed milk.

The deep-frying of *Gulajamun* was conducted using a commercial deep fryer, as shown in Fig. 2a. The deep fryer was filled with two litres of *Ghee* and heated to a consistent frying temperature. Then, the balls (10 no.) were placed in the *Ghee* for deep frying at *a Ghee* temperature of 150°C for 10 minutes (Kumar and Manjunatha, 2022). The frying process was done at various times for different samples, as shown in Table 2.

Preparation of sugar syrup

The concentration of the sugar syrup used for dipping the fried *Gulabjamun* balls played a crucial role in achieving the final product's desired sweetness, texture, and shelf life. It was essential for the syrup to have approximately 50–60% total solids to meet these objectives effectively. To prepare the sugar syrup, equal amounts of sugar and water were boiled until the desired concentration was attained. During boiling, any dirt or impurities accumulated on the syrup's surface

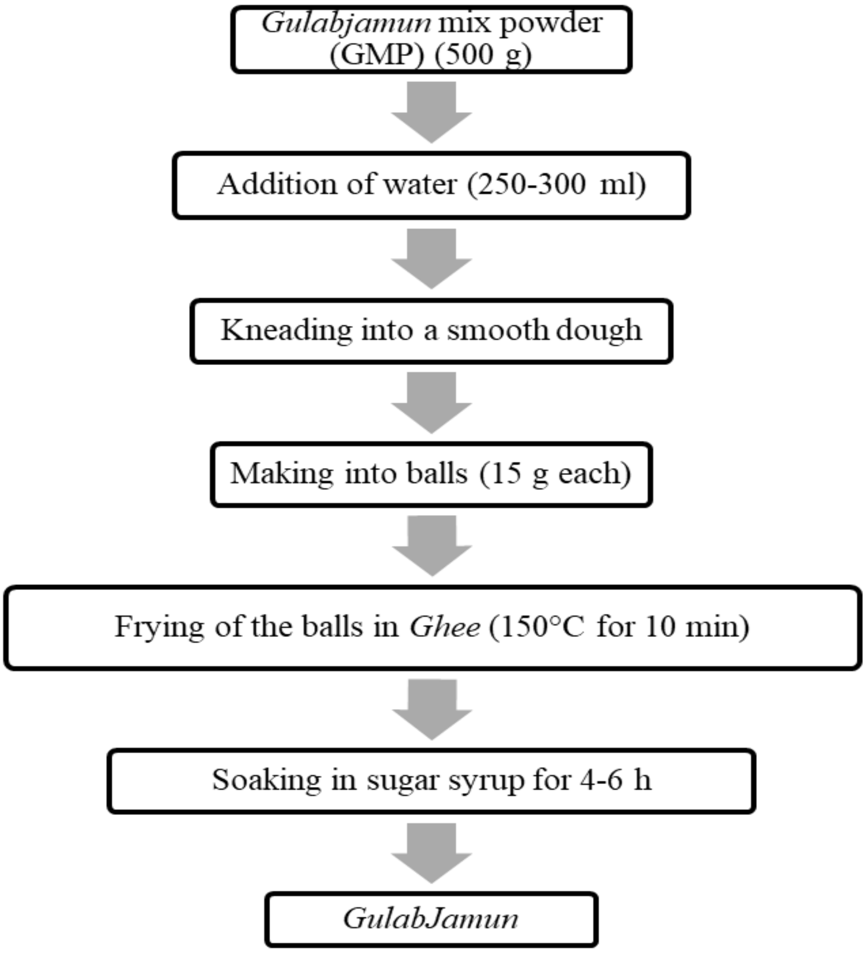

Fig. 1. *Flow diagram of Gulabjamun prepared from Gulabjamun mix powder*

Table 1. Formulation of *Gulabjamun* mix from roller-dried skimmed milk

Ingredients	Percentage
Roller-dried skimmed milk	43.4
Maida	25.0
Suji	15.0
Vanaspati Ghee	15.0
Baking Powder	1.5
Cardamom Powder	0.1

Table 2. Frying time for different samples of *Ghee*

Sample no.	Heating time (hour)
1	4
2	8
3	12
4	16
5	20
6	24
7	28
8	32
9	36
10	40
11	44
12	48
13	52
14	56
15	60

were removed using a perforated ladle. Once the *Gulabjamun* balls (10 pieces) were fried, they were transferred to the sugar syrup (1000 ml) and soaked for 4-6 hours at a temperature of 50°C (Fig. 2b).

Viscosity analysis

The rheological characteristics were conducted on the collected *Ghee* samples using the HAAKE iQ Viscotester. The instrument was set to perform steady-state shear tests, where the shear rate was varied while measuring the corresponding shear stress. The data obtained from the rheometer allowed the calculation of key rheological parameters, including viscosity, shear stress, and shear rate, as adopted by Zakaria *et al.* (2022).

Colour measurement of *Ghee samples*

The Hunter Lab colour system was employed to characterise the colour attributes of the *Ghee* samples. The Hunter colorimeter, calibrated with standard white and black references, was used for colour measurements. The L* value represents lightness, where higher values indicate lighter colours; a* represents the red-green axis, with positive values indicating redness and negative values indicating greenness; and b* represents the yellow-blue axis, with positive values indicating yellowness and negative values indicating blueness and the yellowness index.

The difference in colour parameters between the initial and final samples was made to ensure the colour changes due to the heating time of the *Ghee*, which showed the effect of repeated frying.

RESULTS AND DISCUSSION

Colour analysis of the *Ghee* samples

The L* values indicate the lightness of the *Ghee* after frying the *Gulabjamun*. The data shows that the L* values vary with frying time, ranging from 41.1 (at 4 hours) to 43.07 (at 60 hours of frying). As the frying time increases, the L* values decrease slightly, suggesting that the *Ghee* darkens in colour during the frying process.

The ΔL* value of 1.97333 indicates that Sample 15, fried for 60 hours, appears darker compared to Sample 1, fried for 4 hours. This result suggests that the longer frying duration caused the *Ghee* to darken, resulting in a decrease in lightness (L* value). The detailed colour

Fig. 2a: *Frying of Gulabjamun*

Fig. 2b: *Soaking of fried Gulabjamun*

Fig. 2. *Preparation of Gulabjamun*

analysis is shown in Fig. 3. and Fig. 4.

A similar finding was observed in Khaja, a traditional sweet in India. Researchers studied the optimisation of Khaja's frying process. The results showed that the lightness of the samples decreased significantly (*$p < 0.05$*) from 68.59 to 43.33, which shows the Khaja was getting darker as the frying proceeded (Kumar *et al.,* 2022a).

The ΔL* values represent the lightness of the product. The data indicates that the L* values consistently decrease as the frying time increases. This suggests a shift towards darker hues in the *Ghee* after frying the *Gulabjamun* for longer durations. The Δa* value of -7.22334 indicates a shift towards green hues in Sample 15 compared to Sample 1. This suggests that the longer frying duration, the Ghee's redness, resulting in a more pronounced green tint. The Δb* value of 0.66666 indicates that Sample 15 has a slightly stronger yellow hue than Sample 1. The increase in the Δb* value suggests that the longer frying duration caused the *Ghee* to develop a more intense yellow colour.

Similarly, a study by Gomes *et al.* (2021) used spray drying to characterise the morphology of whey protein concentrate (WPC) admixture with microencapsulated curcumin. The data shows that the b* values increase with frying time, indicating a stronger yellow colour in the *Ghee* after longer frying durations. This increase in the b* values suggests that the frying process leads to the development of a more intense yellow colour in the *Ghee*. Similarly, Buchilina and Aryana (2021) studied the colour analysis of camel milk yoghurt to determine the effect of sweeteners on it. The result showed an increasing trend similar to our study.

The yellowness values also show an increasing trend as the frying time increases. This is consistent with the increase in the b* values, indicating that the yellowness of the *Ghee* intensifies with longer frying durations. The Δyellowness value of -10.72 indicates a significant decrease in yellowness for Sample 15 compared to Sample 1. This result aligns with the changes in the Δb* value, indicating that the longer frying duration reduced the yellowness of the *Ghee*.

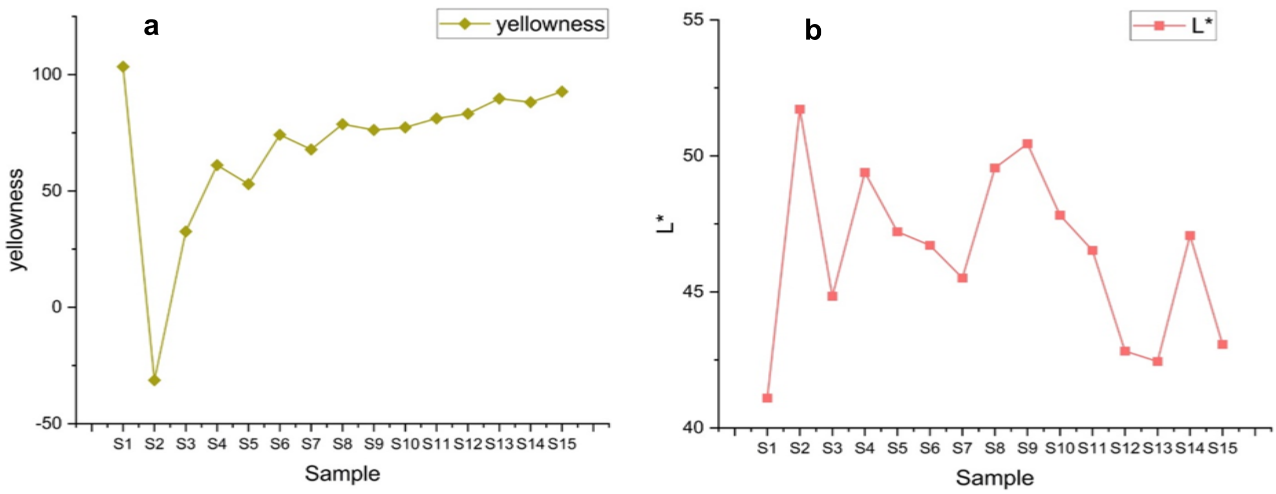

Fig. 3. *Color values for various samples:* ***a.*** *Yellowness index for various samples;* ***b.*** *Lightness (L*) for various samples*

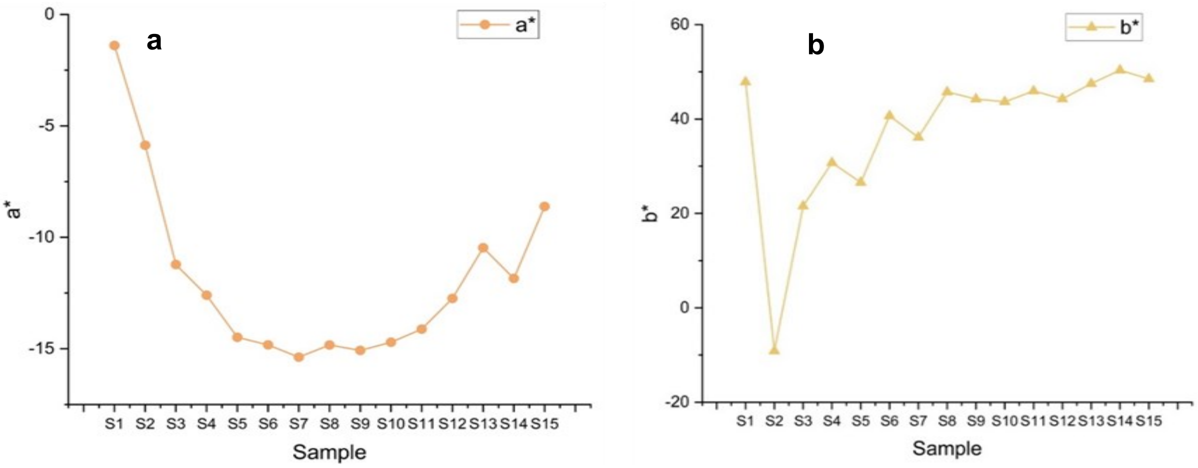

Fig. 4. *Unique colour coordinates for various samples:* ***a.*** *Red/green coordinates (a*) for various samples;* ***b.*** *Blue/ yellow coordinates (b*) for various samples*

Heating has an effect not only on the yellowness of a product but also on the yellowness index. Chakravartula *et al.* (2019) observed that the higher concentration of pectin and whey protein concentrate increases the yellowness index. The changes in colour properties, particularly the decrease in lightness (L*) and the increase in yellow hue, indicate the Maillard reaction occurring during the frying process. The Maillard reaction is a complex chemical reaction between reducing sugars and amino acids in the *Gulabjamun*, forming browning compounds. These browning compounds are responsible for developing a darker colour and a more intense yellow hue in the *Ghee* as the frying time increases (Bai *et al.*, 2022; Shi *et al.*, 2023). Similarly, Wang *et al.* (2021) studied the colour properties of whey protein. The findings revealed that increasing the Maillard reaction rate might diminish the lightness of protein cooked with reduced sugar products. The L* value, and the a* value of whey protein was raised because of the heat treatment, which causes significant redness. Furthermore, heat treatment raised the b* value of whey protein and Maillard reaction products, signifying an increase in yellowness.

The variations in colour properties are influenced by the temperature and frying time. Higher temperatures and longer frying durations provide more time for the Maillard reaction to occur, leading to greater colour changes in the *Ghee*. The duration of the frying process allows for the accumulation of browning compounds, resulting in the observed colour shifts (Sangama *et al.*, 2023; Yokogawa *et al.*, 2023). The frying process can lead to the degradation of pigments naturally present in the *Gulabjamun*. As the *Gulabjamun* fries in the *Ghee*, these pigments may undergo changes due to heat and interaction with the *Ghee*, contributing to the observed alterations in colour properties (Battula *et al.*, 2020; Panwar *et al.*, 2023).

The changes in the Ghee's colour properties result from various heat-induced chemical reactions, including the Maillard reaction, caramelisation, and other thermal degradation processes. These reactions are influenced by the specific composition of the *Gulabjamun*, the type of *Ghee* used, the frying temperature, and the frying time. The observed colour changes can indicate the degree of browning and flavour development during frying, contributing to the overall sensory experience of the fried *Gulabjamun*.

Viscosity analysis of the ghee samples

As the *Gulabjamun* is fried in the *Ghee*, several complex chemical reactions take place, leading to changes in the *Ghee*'s viscosity. These changes are influenced by various factors, including the temperature, frying time, type of food being fried, and the composition of the *Ghee*.

Ho *et al.* (2022) stated in their study that heat treatment at high temperatures and short time led to a significant increase in viscosity in milk protein concentrates. Similarly, results were observed in the present study. The shear stress and viscosity values of the *Ghee* where *Gulabjamun* was fried were not consistent throughout the heating process. The changes in viscosity indicate that frying the *Gulabjamun* in the *Ghee* leads to alterations in the fluid's resistance to flow. As the frying time increases, the viscosity of the *Ghee* varies, suggesting that the frying process affects the *Ghee*'s flow characteristics. A similar study was done by Patel *et al.* (2022) on ghee characteristics on heating, they also found that the g*hee* viscosity increases as the heating time increases.

The viscosity of all liquid milk protein concentrates decreased with increasing shear rate, showing non-Newtonian shear thinning behaviour, as previously reported in the literature studies (Ho *et al.,* 2019). However, in the case of heating g*hee*, it was observed that the viscosity had a nonlinear curve with increasing shear stress. This proved that the viscosity of *Ghee* used for frying was not proportionally related to shear stress. During frying, the *Ghee* is exposed to high temperatures, which can cause thermal degradation of its components. Triglycerides, which are the main constituents of *Ghee*, can undergo hydrolysis and thermal breakdown, resulting in the formation of free fatty acids and glycerol. These changes in the *Ghee*'s composition can influence its viscosity. Additionally, prolonged heating can lead to oxidation of the *Ghee*, where unsaturated fatty acids react with oxygen to form oxidative compounds. Oxidation can increase the viscosity of the *Ghee* and affect its sensory characteristics and shelf life.

When heated, the Maillard reaction is a non-enzymatic browning reaction occurring between reducing sugars and amino acids. As the *Gulabjamun* is fried, the Maillard reaction generates a wide range of browning compounds, such as melanoidin and other flavour and aroma molecules. These compounds presence can alter the Ghee's viscosity by interacting with its components. In the case of extended heating of chocolate, Maillard browning also changes the product's viscosity (Rodier and Hartel, 2021).

The *Ghee* appeared to reach its peak viscosity at 12 hours of heating, where the shear stress was highest (19.10 Pa) and the viscosity was at its maximum (0.66 Pa-s). During the frying of *Ghee*, the peak viscosity is observed at around 12 hours of heating. This peak viscosity can be attributed to various factors that come into play during the initial stages of frying. Firstly, as the *Gulabjamun* is added to the hot *Ghee*, moisture present in the *Gulabjamun* undergoes rapid evaporation, forming steam bubbles in the *Ghee*. The presence of steam bubbles creates resistance to flow, resulting in higher shear stress and increased viscosity.

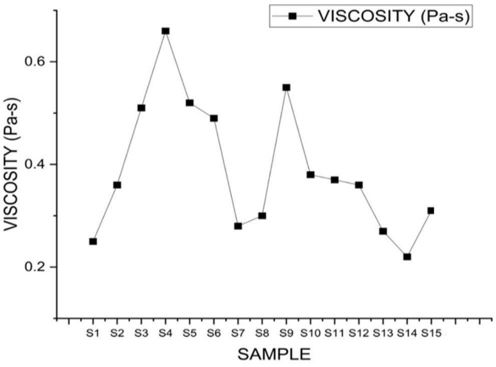

Fig. 5. *Viscosity for various samples*

As the *Gulabjamun* fries, a crust starts forming on its surface. This crust acts as a physical barrier, reducing direct contact between the *Ghee* and the *Gulabjamun*. Consequently, the rate of water evaporation is reduced, which, in turn, decreases the formation of steam bubbles in the *Ghee*. This process contributes to the *Ghee* reaching its maximum viscosity at around 12 hours of frying.

The fluctuations in viscosity observed during frying can be attributed to the dynamic nature of the frying process. As the *Gulabjamun* is added to the hot *Ghee*, the water content in the food undergoes rapid evaporation, leading to changes in the *Ghee*'s consistency. The release of steam and other volatile compounds from the food can affect the *Ghee*'s flow characteristics and result in transient variations in viscosity (Patel *et al.*, 2022). As *Ghee* is reused for frying multiple batches of *Gulabjamun*s, the viscosity changes may become more pronounced. Repeated heating cycles can accelerate the degradation of the *Ghee*, leading to higher viscosity due to the accumulation of degradation products and polymerisation of fatty acids (Nawaz *et al.*, 2023). Regularly monitoring viscosity during *Ghee* reuse can help determine the appropriate time for *Ghee* replacement to maintain product quality. Similarly, Mishra *et al.* (2023) studied on different changes upon heating of cooking oils, they indicated that the viscosity was lower before heating (in fresh oil) than after repeated heating in all oil samples. The oil's viscosity reached between 690.32 and 740.32 millipoise from 638.26 to 648.32 millipoise after 10 cycles of repeated frying. After five batches, the viscosity was determined to be between 670.23 and 720.12. The rise in viscosity is most likely due to hydrogenation's saturation of the triglyceride chain, whereas the reduction is most likely due to oil's unsaturation. The higher the percentage of unsaturated oil (liquid at room temperature), the lower the viscosity. (Santos *et al.,* 2014).

After reaching the peak viscosity, there is a slight decrease in both shear stress and viscosity as the heating time progresses beyond 32 hours. The breakdown of triglycerides into smaller molecules and the formation of long-chain polymers cause a change in the *Ghee*'s molecular structure, making it less viscous. The polymerisation was accelerated by the high temperatures during frying. As polymerisation proceeds, the *Ghee*'s molecules become larger and more complex, reducing the *Ghee*'s viscosity. The polymerised compound also increases due to polymerisation reactions. So, it increases viscosity as long-chain compounds are not moved easily (Santos *et al.,* 2005).

Figures 5 and 6 show the viscosity curves for the frying *Ghee* samples. The combination of thermal degradation and polymerisation contributes to the observed decrease in shear stress and viscosity of the *Ghee* as the frying time progresses beyond 32 hours. The breakdown of triglycerides into smaller molecules and the formation of long-chain polymers cause a change in the *Ghee*'s molecular structure, making it less viscous.

Conclusion

The comprehensive examination of colour and viscosity changes illuminated the complex transformations in both the dessert and the frying medium during the frying of an Indian recipe *Gulabjamun* in *Ghee*. The colour analysis revealed that the values for lightness (L*), red-

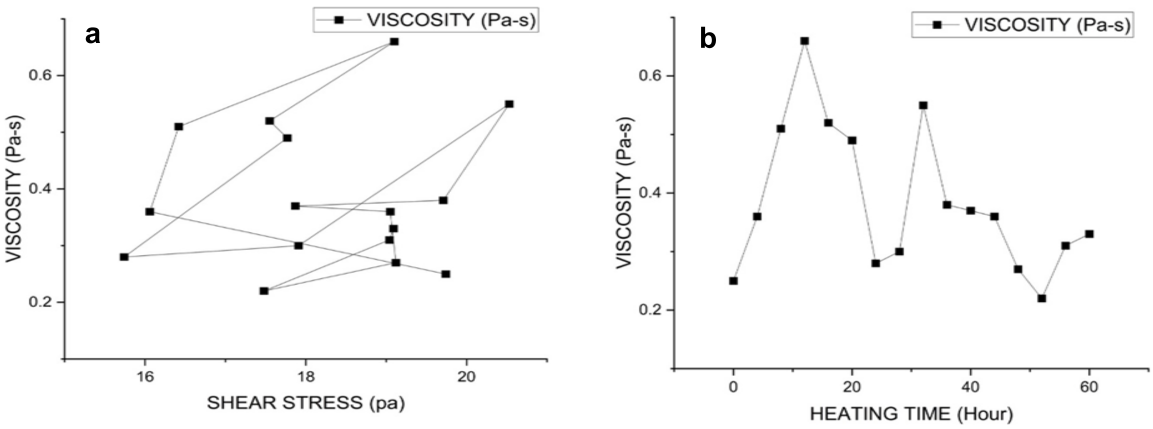

Fig. 6. *Viscosity curves for frying Ghee samples with respect to shear stress and heating time:* ***a.*** *Viscosity vs shear stress curve;* ***b.*** *Viscosity vs. heating time curve*

green (a*), and yellow-blue (b*) changed dynamically across a spectrum of frying times. These changes resulted from chemical reactions triggered by heat, such as the non-enzymatic browning process known as the Maillard reaction, which generates browning chemicals and alters the colour of the *Ghee*. The *Ghee* becomes darker, the green hues become more prominent, and the yellow hues become more intense the longer it is fried. As the frying process continued, the viscosity of the *Ghee* demonstrated intricate changes in its flow properties. The viscosity changed as moisture evaporated and steam droplets formed early on in the frying process. The *Ghee* attained the maximum viscosity after 12 hours of frying, which was correlated with the formation of a scum and the disappearance of steam bubbles. However, after 32 hours of frying, the viscosity decreased due to the degradation of triglycerides and the formation of long-chain polymers. These findings also contribute to understanding the chemical changes occurring when heated edibles. Thus, the study could understand how frying affects both the dessert and the frying medium.

ACKNOWLEDGEMENTS

The authors thank the Director-NDRI and Head-Dairy Engineering Division, ICAR-NDRI, Karnal, for providing the lab facilities for conducting this research.

Conflict of Interest

The authors declare that they have no conflict of interest.

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