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RESEARCH ARTICLE

Computational fluid dynamics (CFD) simulation and experimental validation of thermal and quality dynamics in fried *Gulabjamun*

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Abstract: *Gulabjamun* is a traditional Indian dairy product and is a sweet delicacy which is popular across the South Asian countries. However, its production is mostly done at small scale by unorganized dairies due to the lack of process equipment available for its production. Modelling and simulation are considered useful tool for designing and optimizing the process parameters for equipment design. Thus, present work focuses on simulation of temperature distribution across the *gulabjamun* ball during frying at different temperatures using ANSYS R15.0 software. Validation of the simulated results was done by conducting the frying and the results given by simulation and actual experiment were comparable. The effect of frying temperature and time on the thermal conductivity, specific heat and change in weight and volume were measured. The hardness value of fried *gulabjamun* varied from 2156 to 2975 g force increasing temperature from 120°C to 140°C as analysed using texture profile analyser. Based on the different quality parameters, temperature time combination of 130 for 20 min was selected as optimum combination for frying of *gulabjamun* balls.

Keywords: Free fatty acid, *Gulabjamun*, Mathematical modelling, Peroxide value, Simulation, TPA

Introduction

Frying is the most convenient, easy and effective method of food preparation employed all over the world for various traditional cuisines. It is a process of cooking food in vegetable/animal fat at a high temperature ranging between 150°C to 190 °C. Frying can be classified into three categories based on the quantity of frying medium used, which includes sautéing (little fat in the pan), shallow frying (fat comes partly up the sides of the food) or deep fat frying (food completely dipped in fat). Heat transfer during frying, resulted in structural and chemical changes in the components of food such as gelatinization of starch, denaturation of proteins and softening of food fibres, thus imparting typical flavor, color and texture to fried food (Miranda and Aguilera 2006).

Ghee (clarified butter), an ancient Indian product widely consumed and popular milk product in the Asian, Middle-east and African households, is derived from the sanskrit word *Ghrita* (Hazra *et al*. 2017). *Gulabjamun*, is a popular traditional Indian dairy product, prepared from *Khoa* (heat desiccated semi solid mass of milk) and *maida* (refined wheat flour) using deep fat fraying in a frying pan (*Karahi*) with an appropriate frying medium (preferably *ghee* for better flavor) at 120-130°C. However, besides the popularity, it is being prepared at small scale by unorganized dairy sector because of the lack in processing equipment's for deep fat frying. This gap in processing could be attributed to the requirement of the analysis of heat and mass transfer processes during deep fat frying. Many thermal and mass transfer constants need to be quantified in order to optimize the process for *gulabjamun* processing at large scale commercially. For that purpose, modelling and simulation come at ease of process engineers.

Modelling and simulation are based on mathematical models that describe the dynamics of any process (Neethu *et al*. 2016). Modelling and simulations are increasingly being used in the food industry to develop and optimize the products and processes (Moreira *et al.* 1997; Velez Ruiz *et al.* 2002; Sosa-Morales *et al.* 2006; Taiwo *et al.* 2007, Ghodki and Goswami 2019, Ghodki *et al.* 2020). Simulations have many benefits, as being able to assess the effects of various process conditions on the product quality before actually conducting the experiment. Computational Fluid Dynamics (CFD), a simulation-based approach, employs mathematical algorithms and numerical techniques to analyze fluid flow in open as well as closed systems. CFD starts with dividing the region into consideration into many small elements (mesh generation), each of which is assigned flow properties such as mass, velocity, pressure, and temperature. The known

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values of these properties at the boundaries of the fluid region are set as boundary conditions and applied to the respective cells. The software runs the basic equations (continuity equation, Navier–Stokes equations, first law of thermodynamics) for each element based on the boundary conditions and solves them iteratively, thus producing the flow property values for each element. The software combines the result of these equations for each element and gives the overall flow of the heat/mass through the system.

In view of this, the present study aimed to model heat transfer phenomena of *gulabjamun* frying using CFD simulation at three different temperatures (120, 130 and 140 °C) and time (10 and 20 min) combinations. The changes in physical properties of the *gulabjamun* balls before and after frying were also studied.

Materials and Methods

Ghee (Supreme Agri-foods Pvt. Ltd.)*, maida* (refined wheat flour), baking powder, and sugar for frying of *gulabjamun* were procured from local market of Ludhiana, Punjab, India. Freshly prepared *khoa*, was procured from Kamal Dairy, Dairy Complex, Hambran road, Ludhiana, India. Analytical grade (AR) chemicals were used for the preparation of different reagents used for the analysis of *ghee* and *gulabjamun* samples.

The procedure for preparation of *gulabjamun* standardized by Kumar *et al.* (2006) was adopted for this study. The dough for making *gulabjamun* balls was prepared by mixing the ingredients, that is, *khoa*, *maida* and baking powder in fixed quantities. *Ghee* was heated in an iron base vessel/*Kadhai* and the prepared *Gulabjamun* balls were carefully immersed into the hot *Ghee* bath. The *Gulab jamun* balls were fried at three different temperatures, i.e., 120±1 °C, 130±1 °C & 140±1 °C for two different time periods of 10 min and 20 min, until a golden-brown crust was obtained using pan and gas stove.

For measuring the volume of *gulabjamun* balls before and after frying, diameter of the *gulabjamun* balls was measured using vernier calliper. The volume was measured using the formula

$$V = (4/3 \times \pi \times r^3) \quad \text{(Eq. 1)}$$

Table 1: Methodology used for simulation of *gulabjamun* (ball) frying

Case	Initial and boundary conditions	Mesh type	Solver	Model/Process (ANSYS, 2013)
Frying of *Gulabjamun* in *ghee* using pan at 120ºC of *ghee* for 10 minutes	*Gulabjamun* Initial Temperature = 28 ºC The Heat flow through stove = 15 W The ambient temperature = 30 º C	Relevance Centre-Medium Mesh Size = 0.5mm Method= Tetrahedrons	Ansys 15.0 Transient thermal	Energy equation and heat transfer equations Convection through *ghee* to *Gulabjamun* Heat flow from stove to pan Conduction within *Gulabjamun*
Frying of *Gulabjamun* in *ghee* using pan at 130ºC of *ghee* for 10 minutes	*Gulabjamun* Initial Temperature = 28 ˚C The Heat flow through stove = 20 W The ambient temperature = 30º C	Relevance Centre = Medium Mesh Size = 0.5mm Method = Tetrahedrons	Ansys 15.0 Transient thermal	Convection through *ghee* to *Gulabjamun* Heat flow from stove to pan Conduction within *Gulabjamun*
Frying of *Gulabjamun* in *ghee* using pan at 140ºC of *ghee* for 10 minutes	*Gulabjamun* Initial Temperature = 28 ˚C The Heat flow through stove = 24 W The ambient temperature = 30 ˚C	Relevance Centre-Medium Mesh Size = 0.5mm Method - Tetrahedrons	Ansys 15.0 Transient thermal	Convection through ghee to *Gulabjamun* Heat flow from stove to pan Conduction within *Gulabjamun*
Change in volume of *gulabjamun* while frying	Density= 1140 kg/m^3 Volume = 0.000025 m^{3}Velocity inlet of ghee to *Gulabjamun* = 0.1 mm/s^2	Relevance Centre-Fine Mesh Size = 0.3mm Method - Hexagon	Ansys 15.0 Fluent	Laminar Model Energy equation with porous zone having porosity = 1

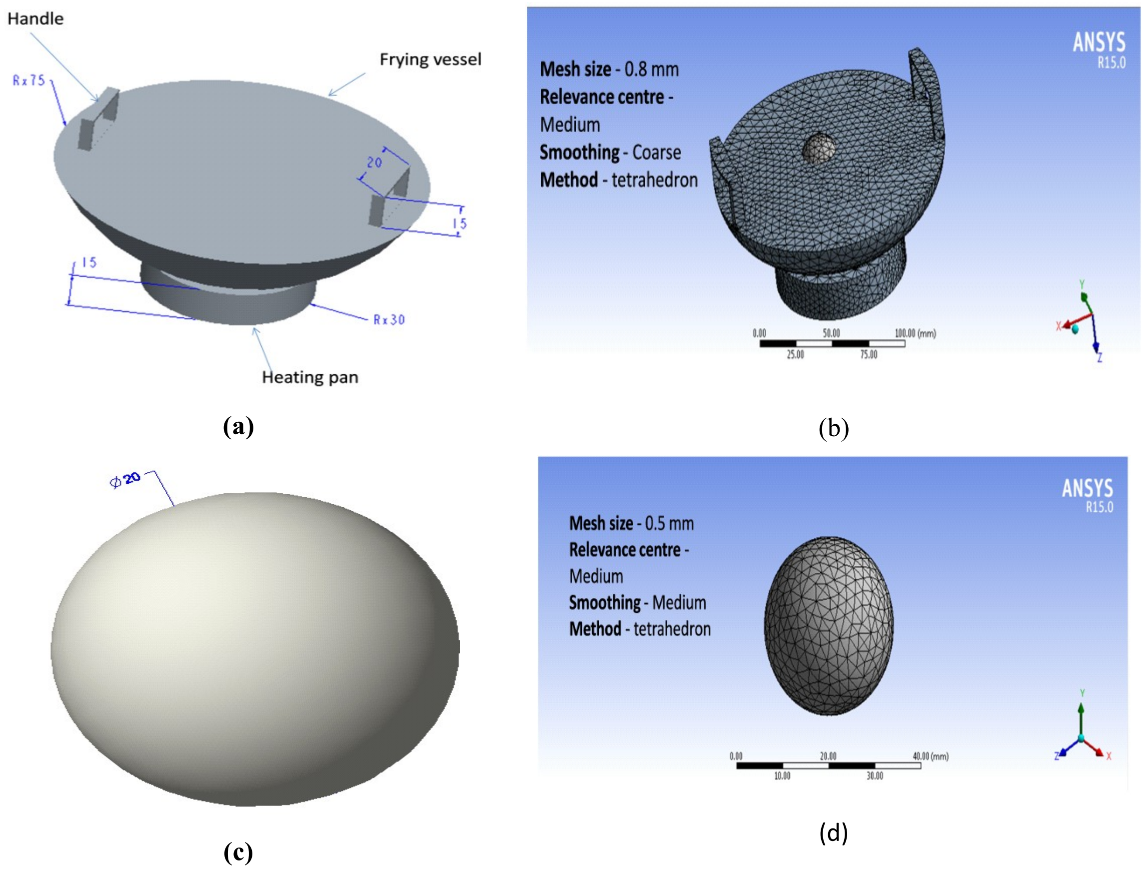


Fig. 1 a) Frying vessel design with dimensions, **b)** Frying vessel meshing with details, **c)** *Gulabjamun* design with dimension and **d)** *Gulabjamun* meshing with details

Where, V = volume of the ball (m^3) and r = radius of the ball (m).

CFD Modelling: Heat transfer modelling of *gulabjamun* frying was performed using Ansys Workbench 15.0 software (Canonsburg) with the transient thermal solver module. Understanding the geometry of the whole system for frying was the first step of the study. The geometry of the system including the frying vessel, the balls and the cooking solution was created using CREO Software (PTC's Creo parametric 3.0). Fine meshing was then done to divide the geometry into fine segments to study the temperature distribution at each and every portion of the geometry. Triangular mesh was used in the geometry with a mesh size of 0.5 mm (Fig. 1a, b, c & d). The mesh size was taken based on grid independence analysis. This step was followed by defining the boundary conditions for the system under consideration. The initial boundary conditions considered were an initial *gulabjamun* temperature of 28 °C, heat flow through the stove as 15 W and an ambient temperature of 30 °C as shown in Table 1. The thermal conductivity of *gulabjamun* dough was taken as 0.340 W/mK from literature (Sharanbasava *et al.* 2018). The system was used to solve the energy and heat transfer equation including convection equation from ghee to *gulabjamun* and conduction for heat transfer for heating within *gulabjamun*. The simulations results were used for analysis of core temperature and volume enhancement of the balls after frying at different frying temperature and time combination.

Core temperature of *gulabjamun* balls during frying was measured by inserting thermometer probe (ST-9283, Multi thermometer probe, Frontier, USA) into the core of *gulabjamun* and recording the temperature values during the complete frying process. Using the simulation results obtained by heat conduction, core temperature and volume enhancement of the balls after frying were analysed at different temperature and time combinations. The detailed methodology used simulation of *gulabjamun* frying is shown in Table 1.

Colour measurement was done using image analysis software. The system composed of controlling unit viz. Raspberry Pi 4 Model B, the Raspberry Pi camera module V2 (with Sony IMX219 8-megapixel sensor) and an HDMI display as hardware components. Python and Open-CV software (Open-source computer version) were used for analysis. The program was developed to grab the frames (Fig 3.4a) from the live video stream of the camera using open-CV and python programming environment. *Gulabjamun* ball before frying was taken as a reference to compare the colour of *gulabjamun* ball after frying at different temperature and time. Images of the fried balls were captured at each temperature and time combination. The histograms were studied to compare the colour values of fired *gulabjamun* balls at different temperature and time combination.

Stable micro systems TAHD+ texture analyzer was used for texture profile analysis (TPA) of fried *gulabjamun* balls. A P36R cylindrical probe was used with 2 mm/s pre-test and 5 mm/s post-test speed. 50% compression was taken for TPA analysis. TPA is a two-bite test, which shows first and second compression cycles. The first and second compression cycles indicate the force versus time plot during the first and second compression of the food product by the instrument probe. The parameters recorded were hardness, springiness, cohesiveness, gumminess and chewiness (Patil *et al.* 2018).

Hardness (N): The maximum peak force measured during first compression.

Cohesiveness: $\frac{\textit{Area underneath the second compression curve}}{\textit{Area underneath the first compression curve}}$ (Eq. 2)

Chewiness: Hardness × cohesiveness × elasticity (Eq. 3)

Gumminess: Hardness × cohesiveness (Eq. 4)

Springiness: $\frac{\text{Distance 2}}{\text{Distance 1}}$ (Eq. 5)

Springiness is also expressed as the percentage of product's recovery to its original height.

Results and Discussion

The results of simulation studies, validation of simulation results with experimental procedures and other properties of *gulabjamun* frying including colour and texture are discussed below.

Heat transfer simulation and validation: The heat transfer took place from the vessel to frying medium through conduction and consequently to the *gulabjamun* balls via convection currents. Heat transfer from the from the surface to the core inside the ball took place by conduction. When frying proceeded, with increasing outer temperature the core temperature increased to a maximum temperature. The temperature profile distribution obtained using simulation from CFD are depicted in Fig. 2. For validation of the core temperature obtained from simulation, a temperature was recorded using a thermometer in the centre of balls.

Core temperature: The temperature at the centre/core of the *gulabjamun* balls indicate the cooking of the ball internally. Core temperature can indicate whether cooking is done properly or not. If cooking is not done properly, core will be hard even after immersing the balls in sugar syrup. A very important factor for proper cooking till the core is outer temperature. If cooking is done at higher temperature, crust formation takes place which prevents the conduction of heat to the centre, resulting in hard inner core. Fig. 2 shows the temperature distribution inside the balls with varying surface temperature. The core temperature obtained from simulation was 96 °C for a surface temperature of 120 °C, 99 °C for an outer temperature of 130 °C and a maximum of 100.4 °C for an outer temperature of 140 °C (Fig. 2b). With increasing frying temperature, core temperature of the *gulabjamun* balls was found to increase and was more than 90 °C ensuring cooking of the balls from the centre giving a soft core. However, there was no significant difference between the core temperatures with varying outer temperature.

Experimentally, the core temperature was recorded by inserting thermocouple probe into the *gulabjamun* ball during frying. The core temperature obtained practically was correlated with the results of simulation. A maximum of 100 °C was recorded at the core with the thermocouple probe at the highest frying temperature of 140±1 °C. Minimum core temperature observed was 96 °C at the frying temperature of 120±1 °C were observed in the simulated model. The core temperature values were validated for 20 min. The simulated results were found consistent with the experimental results. Franklin *et al*. (2014) have also reported the core temperature to be about 100 °C for cooking of *gulabjamun* using heat and mass transfer modelling.

Oil Absorption and Weight Increment During Frying of *Gulabjamun*: The weight of *gulabjamun* samples was recorded before and after frying using a precision analytical balance. The initial mass of each ball was maintained at 12.20 ± 0.05 g to ensure uniformity across samples. Post-frying weights were measured for each time temperature combination as presented in Table 2. Results indicated that the maximum weight gain occurred at 120 °C, where *gulabjamun* balls exhibited an increase of 2.43 ± 0.005 g after 10 min of frying. Under identical frying duration, the weight gain at 130 °C and 140 °C was 1.66 ± 0.005 g and 1.25 ± 0.005 g, respectively. The observed reduction in weight gain with increasing temperature can be attributed to the phenomenon of crust formation, which develops more rapidly at elevated temperatures and results in a hardened outer layer that limits oil absorption. Similar behaviour has been reported in other deep-fried foods, where surface hardening reduces permeability and consequently lowers oil uptake (Krokida and Maroulis, 2001; Bouchon, 2009). At a constant temperature, a progressive increase in frying time led to higher weight gain across all temperature levels, indicating a time-dependent enhancement in oil absorption. This may be explained by increased capillary action and extended exposure of the food matrix to the frying medium, which facilitates greater ghee penetration into the porous structure (Saguy & Dana, 2003; Rimac-Brnčić *et al.* 2004). The higher oil absorption at 20 min of frying consequently resulted in greater mass increment.

Changes in the volume of fried *gulabjamun* balls are summarized in Table 2, with variations ranging between 9.41 mm³ and 61.61 mm³. A similar trend was observed for volumetric expansion as a function of temperature and time. At 120 °C, where crust formation was minimal, the outer surface remained soft, enabling greater ghee absorption and consequently more pronounced volumetric expansion compared to higher temperatures (130–140 °C). The development of a hardened crust layer at elevated temperatures, a process often referred to as case hardening, restricted ghee uptake and limited expansion. For instance, after 10 min of frying, volume changes at 120 °C, 130 °C, and 140 °C were 37.97 mm³, 11.01 mm³, and 9.41 mm³, respectively. Prolonged frying time at a given temperature further enhanced volume change, consistent with the increased immersion time and oil absorption in the product matrix (Moreira *et al.* 1999).

Overall, the findings indicate that both temperature and frying duration significantly influenced oil absorption and structural expansion in *gulabjamun*. Lower frying temperatures promote softer crust formation and greater oil uptake, whereas higher temperatures accelerate crust hardening, leading to reduced weight and volume changes.

Colour Changes in *Gulabjamun* During Frying: Image-Based Analysis

Colour development in *gulabjamun* samples during frying was evaluated using digital image analysis. Images of *gulabjamun* balls fried under various temperature–time combinations were analyzed using image processing software to generate RGB (Red, Green, Blue) colour histograms (Fig. 3a–f). The pre-fried samples served as the colour reference standard for comparative analysis. The RGB histograms revealed distinct colour variations across different frying temperatures and durations, indicating progressive browning of the product. At 120 °C and 20 min of frying, the red pixel intensity was recorded at approximately 153,000, while corresponding values at 130 °C and 140 °C were 160,000 and 169,000, respectively (Fig. 3b, 3d, 3f). The dominance of red channel intensity over green and blue channels demonstrated that the fried *gulabjamun* samples exhibited a deeper brown hue with minimal bluish or greenish tones. The increasing red pixel intensity with rising temperature suggests enhanced Maillard reaction and caramelization phenomena, which are known to intensify browning in fried and baked foods (Fennema, 1996; Maskan, 2001). Similar findings were reported by Kumar *et al.* (2006) in their study on colour and texture changes

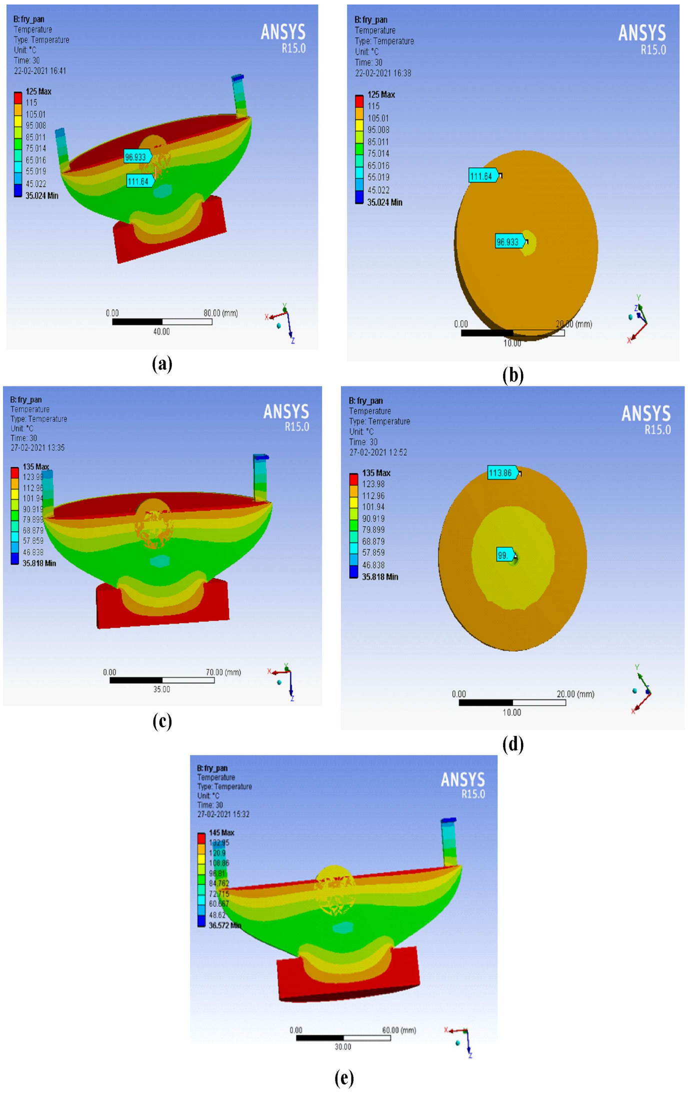
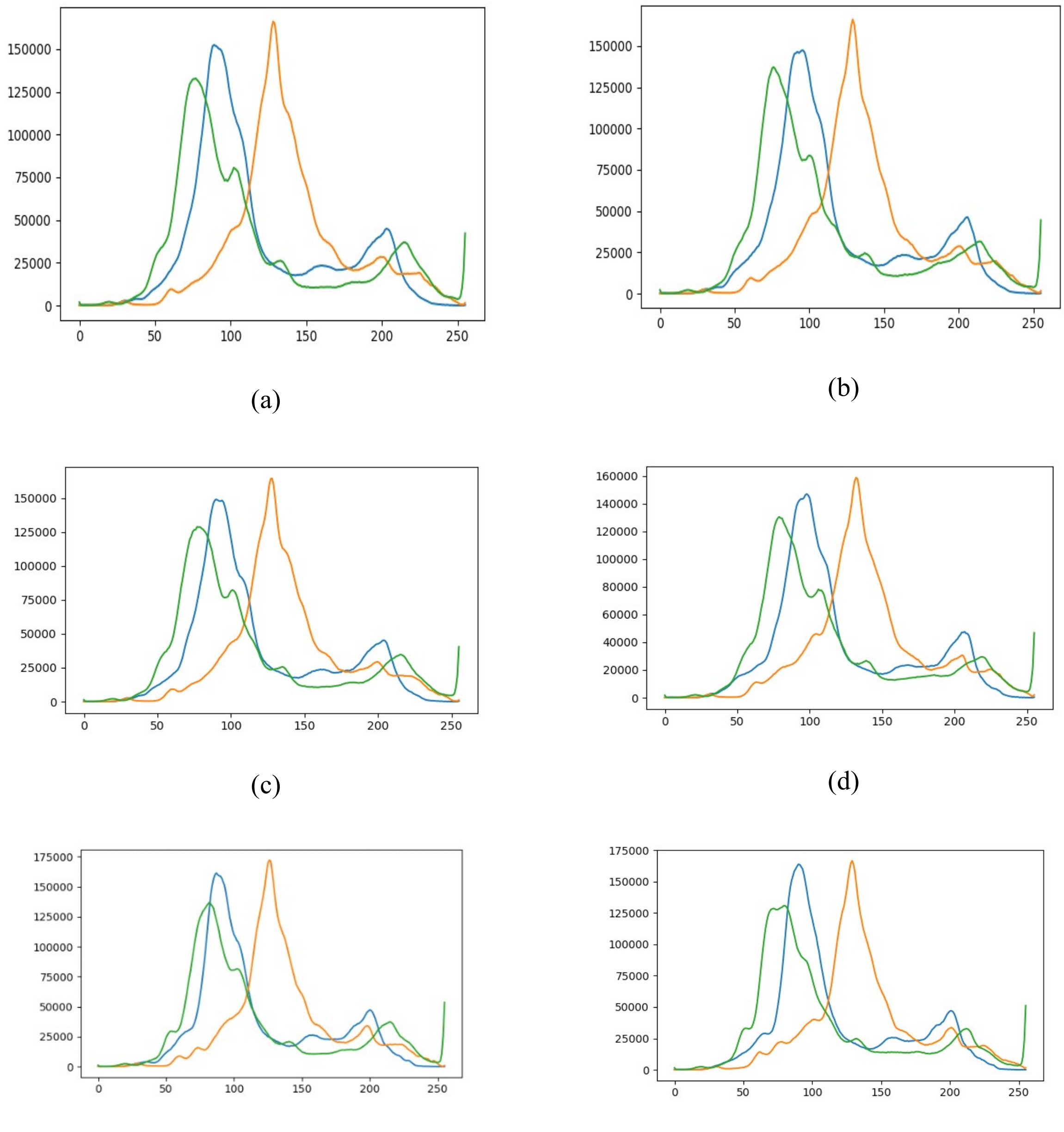


Fig. 2 Temperature distribution curves of gulabjamun ball frying at **(a)** 120 °C **(c)** 130 °C **(e)** 140 °C and core temperature of gulabjamun **(b)** 120 °C **(d)** 130 °C

Table 2: Change in weight in *gulabjamun* balls after frying at different time temperature combinations

Temperature (°C)	Time (min)	Initial weight (g±0.005)	Final weight (g±0.005)	weight gain (g)	Initial diameter (mm)	Final diameter (mm)	Change in volume (mm³)
120	10	12.20	14.63	2.43	26.66	30.83	37.97
	20	12.20	14.87	2.67	26.66	31.56	61.61
130	10	12.20	13.86	1.66	26.66	29.42	11.01
	20	12.20	14.62	2.42	26.66	29.85	16.84
140	10	12.20	13.45	1.25	26.66	29.28	9.41
	20	12.20	13.71	1.51	26.66	29.35	10.19

Note: The average values of three replication are reported weight gain data.



(a) (b) (c) (d) (e) (f)

Fig.3 RGB histogram of fried *gulabjamun* ball at **a)** 120 °C and 10 min of frying **b)** 120 °C and 20 min of frying **c)** 130 °C and 10 min of frying **d)** 130 °C and 20 min of frying **e)** 140 °C and 10 min of frying **f)** 140 °C and 20 min of frying

in *gulabjamun* during frying, where higher temperatures led to darker product surfaces.

Furthermore, at a constant temperature, the duration of frying also significantly affected the colour intensity. Samples fried for 20 min exhibited greater red pixel concentration compared to those fried for 10 min, reflecting cumulative pigment formation with longer exposure to heat. This pattern aligns with established trends in fried food colour kinetics, where both temperature and time act synergistically to accelerate non-enzymatic browning (Marquez & Anon, 1986; Yadav & Jindal, 2008).

Overall, image-based colour analysis demonstrated that frying temperature and time have a pronounced influence on the surface colour of *gulabjamun*. The increase in red channel intensity corresponds to enhanced browning reactions, leading to darker surface pigmentation at elevated frying conditions.

Effect of Frying Temperature and Time on the Textural Properties of *Gulabjamun*

Texture Profile Analysis (TPA) was conducted to evaluate the influence of frying temperature and duration on the mechanical properties of fried *Gulabjamun* samples. The analysis was performed using a texture analyzer to determine parameters such as hardness, which serves as an indicator of the structural integrity and surface rigidity of the product. The results revealed that the hardness values were lowest at 120 °C, indicating a softer texture at lower frying temperatures, whereas higher values were observed at 130 °C and 140 °C. Specifically, hardness increased from 2156 g force to 2975 g force for samples fried for 10 min, and from 1273 g force to 1984 g force for those fried for 20 min as the temperature increased. This progressive increase in hardness with rising temperature can be attributed to case hardening, a phenomenon characterized by the rapid dehydration of the outer surface during high-temperature frying, leading to the formation of a rigid crust (Pedreschi *et al.* 2005; Ziaiifar *et al.* 2008). The hardened crust impedes ghee absorption into the inner matrix, resulting in a firmer texture.

Conversely, at lower frying temperatures and longer frying durations, the samples exhibited reduced hardness, reflecting enhanced oil uptake and a more tender structure. Extended frying time allows for greater penetration of ghee into the internal porous network, which softens the product and reduces resistance to deformation (Baumann & Escher, 1995; Dana & Saguy, 2001). Therefore, frying at lower temperatures for longer periods promotes a more desirable soft texture, whereas high-temperature, short-duration frying induces a harder, less absorbent crust. The observed textural variations are consistent with established principles of deep-fat frying, wherein temperature–time interactions dictate moisture loss, oil absorption, and consequent textural properties of fried foods (Moreira *et al.* 1999; Kita & Lisinska, 2005).

Conclusion

The comprehensive study integrating computational fluid dynamics (CFD) simulations, experimental validation, and quality attribute analysis revealed the interdependent effects of frying temperature and duration on the thermal, physical, and sensory characteristics of *Gulabjamun*. Simulation results of heat transfer closely correlated with experimental data, confirming that core temperatures exceeded 90 °C across all conditions, ensuring complete internal cooking. Lower frying temperatures (120 °C) favoured higher oil absorption and greater volume expansion, resulting in a softer texture and lighter surface colour. In contrast, elevated temperatures (130-140 °C) induced rapid crust formation (case hardening), which restricted ghee uptake, increased hardness, and intensified surface browning due to enhanced Maillard and caramelization reactions. Texture profile analysis confirmed that hardness increased with temperature, while extended frying time reduced firmness through enhanced ghee penetration into the product matrix. Image-based RGB colour analysis demonstrated that red channel intensity correlated strongly with frying temperature and time, validating its potential as an indicator of browning progression. Overall, the findings emphasize that controlled frying at moderate temperatures (H”120 °C) with adequate time exposure (H”20 min) yields *Gulabjamun* with optimal internal softness, structural integrity, and desirable golden-brown colour. The validated CFD model can further be employed for process optimization and scale-up studies in traditional Indian sweet manufacturing, enhancing both product quality and energy efficiency.

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Conflict of interest

The authors confirm that there are no potential conflicts of interest associated with this work.

Data availability statement

Research data are not shared.

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