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Investigation on the Suitability of Cake Batter for 3D Printing

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ABSTRACT: 3D Food Printing is a system of defining options for creative personalization, and revolutionizing food production. In spite of the increasing commercial potential for bakery products, no study has yet examined the printability of cake batter. The influence of the incorporation of hydrocolloids on the dimensional stability of the cake batter was investigated. xanthan gum was blended in mass fractions of 0.25% and 0.75%. The rheological and textural properties of the cake batter were measured and 3D printed structures were analysed. The cake batter of control possessed a low consistency index (248.4Pa.s^n) and printed objects deformed and sagged during post-printing. Whereas the cake batter with the addition of 0.75% xanthan gum displayed shear-thinning behaviour, a consistency index (k) of 975.7(Pa.s^n), and good elastic modulus (G′) resulting in excellent extrudability and printability. Printability and rheological properties are mainly influenced by the source of particles and particle content. Good printing precision and shape stability (upto Height = 3cm) were obtained for the cake batter with 0.75% of xanthan gum. The printed objects exhibited smooth shape, and good resolution, and could withstand the shape over time.

Keywords: 3D Food Printing, hydrocolloid, cake batter, consistency index, elastic modulus, textural properties.

INTRODUCTION

3D printing is an additive manufacturing technique that involves laying down consecutive layers of material to create a three-dimensional object (Hao *et al*., 2010). It provides new levels of localised manufacturing that are truly based on digital fabrication via layer-by-layer deposition in three-dimensional space (Yang *et al*., 2017). This technology helps to create customised food without the need for specialised tooling, moulding, or human interaction and allows for creating an unusual and complex shape (Dankar *et al*., 2018). Food designers can use this technology to create some innovative food designs that are impossible to design by hand or with traditional moulds (Liu *et al*., 2017). The manufacturers of bakeries, cafes, and restaurants can use it to produce baked goods like cakes and biscuits with less labour by creating personalised patterns based on the preferences of their customers (Cohen *et al*., 2009). Sugar, gelatine based chocolate, and other food components are utilised to construct the desired shape using this approach (Mantihal *et al*., 2020).

There are numerous food 3D printing technologies. Extrusion-based is the most used method for printing food. The semi-solid food material is extruded as a tiny thread by the printing nozzle, which has three axes of motion *viz,* X, Y, and Z (Liu *et al*., 2018). Foods can be natively printable, or maybe non-printable and may require appropriate pre-processing (such as the addition of hydrocolloids) to make them printable. The stability of 3D objects both before and after printing is a major issue (Hussain *et al*., 2022), that layers must be rigid and strong enough to support both their weight and the weight of subsequent layers without severely deforming or altering shape (Sun *et al*., 2015). When 3D printed objects are processed, additives and recipe control are two techniques that can significantly increase the accuracy of shape (Lipton *et al*., 2010). Purees, gels, and doughs are all combined with structural hydrocolloids to support their structures(Yang *et al*., 2017). The use of hydrocolloids with food ingredients to create printable food products with a variety of textures and flavours (Cohen *et al*., 2009).

Hydrocolloids are effective food additives with several uses because of their ability to interact and bind with water. The most often used ones are starch, xanthan gum, beta-glucan, guar gum, pectin, alginate, carrageenan, and inulin (Funami, 2011). This research aims to investigate the printability of xanthan gum-based cake batter. The impact of hydrocolloid inclusion on the rheological characteristics, printing performance, and textural profile of the product to demonstrate the stability of 3D printed goods.

MATERIAL AND METHODS

A. Materials

Wheat flour (9.2g/100 g protein and10% mc, 0.86% ash),Powdered Sugar, and Eggs were purchased from local grocers of Coimbatore, Tamil Nadu. Cake Margarine (fat) (TSR International New Super Blend), Double-acting baking powder (Bakers Colour& Flavours (INDIA) Coimbatore, Tamilnadu), Cake Gel (IVORY,V Subramanian and CO, Tiruppur, Tamilnadu), Vanilla No 1 (International Flavors & Fragrances India Private Limited, Chennai), and Xanthan Gum (urban platter).

B. Preparation of Cake Batter

Mixing Method. The flour-batter method is used for the preparation of cake batter. The mixture of fat (margarine) is creamed up with an equal proportion of (1:1) flour until a light creamy mass is obtained. Other ingredients namely Eggs, Sugar, Cake Gel, and Vanilla added to a planetary mixer, which is then whisked at a speed of 80 rpm for 3min. Then the mixture is blended in the same container by using a planetary mixer at a speed of 60 rpm for 2-3 min witha priorly prepared creamy mass and remained baking powder and xanthan gum are added.

Steady Shear Measurements. Rheology of the material supply was examined using a parallel plate rheometer (MCR 52 series, Anton Paar Co. Ltd., Austria) with parallel plate geometry with a diameter of 50 mm. The experiments were carried out at 25°C with a 1 mm gap between the two plates. The steady shear viscosity measurements of the samples were recorded by ramping the shear rate from 0.1 to 500 s^{-1}. Once the sample was loaded, the geometry was adjusted to the place of the measurement, and any excess sample was cleared from the edges. The acquired rheological values were fitted to the power-law model to explain how apparent viscosity and shear are related (Eq. 1) (Wilson *et al*., 2020).

$$\eta = k.\gamma^{n-1} \quad (1)$$

where η is the material viscosity (Pa s), γ is the shear rate (s^{-1}), k is the consistency index (Pa s^n), and n is the flow behaviour index (dimensionless).

Oscillatory Dynamic Measurements. A Rheometer (MCR 92 series, Anton Paar Co. Ltd. Austria) was used to measure the dynamic viscoelastic properties of the material supply by a small amplitude oscillatory frequency sweep test. Initially, strain sweeps (0.01 to 100 per cent) at a fixed frequency of 1 Hz were used to calculate the linear viscoelastic range (LVR) of the samples.

At 0.05% strain (in the viscoelastic linear regime) and 25^{o}C, the frequency sweep test was conducted with frequency ranging from 0.1 to 100 rad/s. By measuring the shear storage modulus (G'), which describes the elastic behaviour of the samples, and the shear loss modulus (G"), which describes the viscous behaviour of the sample, dynamic rheological parameters (mechanical spectra) of the samples were recorded. The loss factor (tanδ) was determined by (Eq. 2) (Ronda *et al*., 2011).

$$\tan\delta = \frac{G"}{G'} \quad (2)$$

C. Printing Process

The food-based 3D Printer (Fabforge Innovations Private Limited, Coimbatore, Tamil Nadu) (Fig. 1), is primarily outfitted with four cylindrical metal tubes and an XYZ positioned supplied with a pneumatic extrusion system is propelled by compressed gas. The food components were placed in a plastic syringe which was put into a metal tube. The printing contained four tubes that could be used individually or collectively for four different types of materials (Huang *et al.,* 2019). The syringe barrel was filled with cake batter and composite with gums, and the printing programme was set up. Fusion 360 software was used to build two 3D models (a cylinder, and a mickey mouse), which were then translated using the slicing programme simplify 3D (Simplify3D®, Cincinnati, OH). The following printing settings were made: flow rate 100%, with a rectilinear fill pattern; printing nozzle aperture-1.20 mm; nozzle height- 1.15 mm; printing speed-40 mm/s. These settings were established based on the initial tests. The cylinder and the mickey mouse were printed in the following dimensions 1) cylinder (30 mm in length, width, and height), and 2) Mickey Mouse (w = 35mm, l = 40mm, h = 30mm).

Table 1: The pound cake recipe that Luyts *et al*. (2013) with some modification in ingredients.

Ingredients	Baker's Percentage (%)
Wheat flour (%)	25
Sugar (%)	25
Margarine (fat) (%)	25
Egg (%)	22.5
Cake Gel (%)	1.15
Vanilla essence (%)	1.15
Double-acting Baking Powder (%)	0.37
Level of Xanthan Gum (%) (XG)	0%(Control),0.25%,0.75%

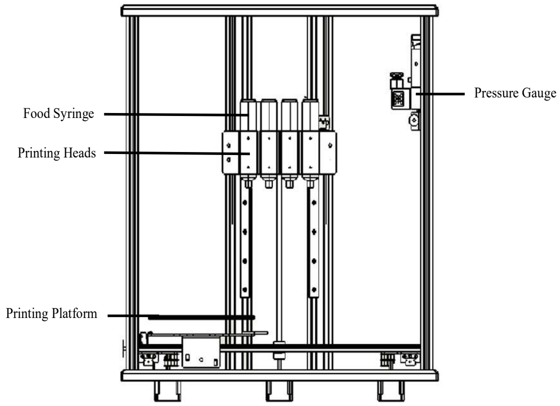


Fig. 1. Schematic view of the 3D Food printer used in this study.

3D Structure Analysis. In this experiment, a cylinder ($30\times30\times30mm^3$) and a mickey mouse (w = 35mm, l = 40mm, h = 35mm) were chosen for printing. The printed cylinder and mickey mouse were measured for length, width, and height using vernier callipers. The research approach of Liu *et al.*, (2019) was used to evaluate the quality of printed samples. During and immediately after printing, images of the printed structures were taken, and the print quality was visually graded on a scale of 1 to 5 (1 = extremely terrible, 5 = very good).

D. Textural Properties of the Prepared Cake Batter

The strength of the mixture was studied by performing a texture profile analysis using a texture analyser (TA-HD plus, Stable Micro Systems Ltd., UK) attached to a cylindrical probe (P/36) by the compression of the cake batter. The initial distance between plate and probe was set to 3.0 cm, 2 mm is the test speed, 3 mm is the pre-test speed, and 10 mm is the post-test speed (Yang, *et al.*, 2018).

RESULT AND DISCUSSION

A. Rheological Behaviour

Steady Shear Measurements. In order to achieve continuous extrusion during 3D printing, food items must be able to flow. By analysing the shear profile and viscosity of the cake batter, the impact of different xanthan gum concentrations on the rheological behaviour of the prepared cake batter was investigated. All materials exhibited shear-thinning behaviour, showing that the material's apparent viscosity decreased as the shear rate increased irrespective of the xanthan gum proportion added. The apparent viscosity curve (Fig. 2) shows that the viscosity of the prepared cake batter decreases as shear rates increases, exhibiting shear-thinning behaviour for n < 1 and k = 248.4, 565.3, & 975.7$Pa.s^n$ for control, 0.25% and 0.75% of xanthan gum respectively. The model demonstrated non-Newtonian behaviour, with all cake batters exhibiting shear thinning behaviour due to enhanced fluidity of the batter matrix brought about by the breakdown of large agglomerated particles into smaller ones (Azari *et al.*, 2020).

The cake batter with 0.75% xanthan gum is thicker than the control because it has a lower flow behaviour index (n = 0.327). This may be because xanthan gum has strong thickening properties, i.e. greater apparent viscosity (195 Pa.s) of the cake batter with 0.75% xanthan gum compared to the control (80 Pa.s). High k values of cake batter with 0.75% xanthan gum indicate that the batter's emulsified structure is rigid. Due to significant water absorption in batters throughout the solubilization, gelatinization, and unfolding processes, which lowers the quantity of free water available in the solution, the cake batter with 0.75% of xanthan gum has high apparent viscosity (Martínez *et al.*, 2015). The steady-state shear measurements that the viscosity decreased as the shear rate increased, indicating that the material supply exhibited the necessary post extrusion behaviour that contributed to structural stability.

Table 2: Values of consistency index, k (Pa s^n), flow behaviour index(n) of material supply.

sample	k	n	R^2
control	248.4	0.484	0.998
0.25% of xanthan gum	565.3	0.383	0.981
0.75% of xanthan gum	975.7	0.327	0.952

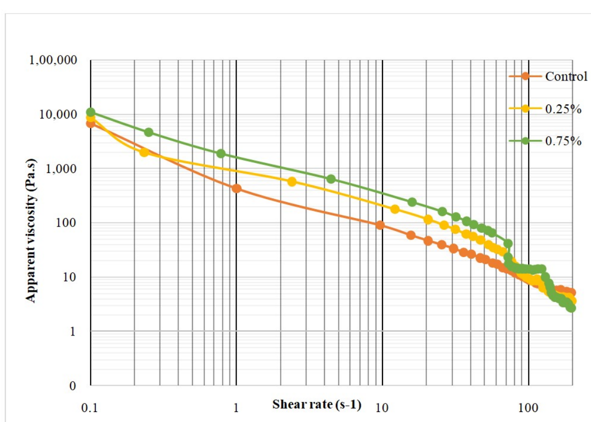


Fig. 2. Apparent viscosity curve of different material supplies.

Dynamic oscillatory measurement. Understanding the flow ability and post-printing stability of material supply is simplified by an evaluation of the dynamic viscoelastic properties. The loss modulus (G") is the viscous response, which is the ratio of stress to strain under vibratory conditions, whereas the storage modulus (G') is a measure of the elastic solid-like behaviour. The loss tangent (tan δ = G"/G') is used as a characteristic parameter to exhibit the different viscoelastic behaviour (Yang *et al*., 2018). A 0.05 % strain rate was selected for the oscillation test in the linear viscoelastic range. In every sample, G' and G" values increased with angular frequency. It was observed that batters behaved solidly because the storage modulus was greater than the loss modulus. All batters' G′ was significantly higher than G″ (Fig. 3), indicating an elastically active gel-like structure that is favourable to the ability of a printed object to retain its shape (Huang *et al*., 2019). The cake batter with 0.75% xanthan gum possesses good printing stability and has G′ (16.70kPa) and G″ (5.95 kPa) values that are higher compared with the control cake batter of G′ (11.16 kPa) and G″ (3.80 kPa) values.

Additionally, the mixing system produced higher inter- and intramolecular pressures as the oscillation frequency, G′ and G″, increased (Liu *et al*., 2020). Based on the results, it is evident that the tan δ for all prepared cake batter was < 1, indicating the elastic nature and the solid-like behaviour of the material supplies (Wilson *et al*., 2020).

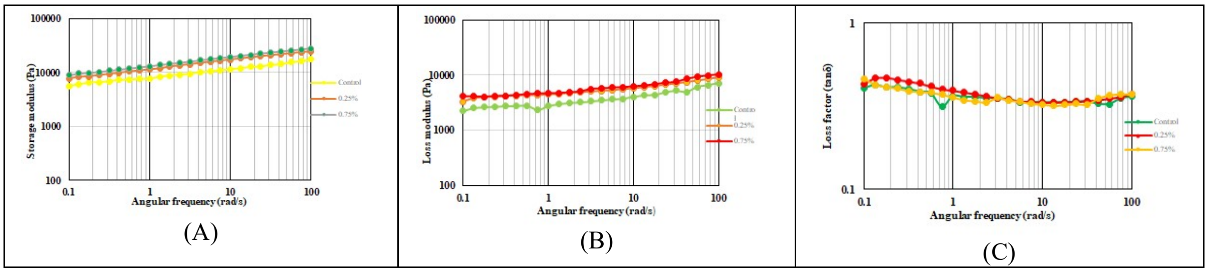


Fig. 3. Dynamic viscoelastic properties of the material supplies. (A) Storage modulus (G′) (B) Loss modulus (G″). (C) Loss tangent (tan δ).

B. Analysis of Textural properties

Assessing the behaviour of the material when subjected to mechanical stress is made easier by analysis of the textural profile of the prepared cake batter. The control, 0.25%, and 0.75% xanthan gum of prepared cake batter hardness, adhesiveness, springiness, cohesion, and resilience were analysed. The amount of extrusion force necessary to push the material out of the print head with a changing cross-sectional area from the syringe feeder to a smaller aperture of the printing nozzle is studied by the hardness of the material supply. The cake batter with 0.75% of xanthan gum exhibited a hardness of (100.21g), which is high compared to the hardness of the control cake batter (87.22g). All samples' hardness significantly increased as hydrocolloid concentrations increased (Kim *et al*., 2017). The characteristic of the material supply known as adhesiveness supports the binding of each printed layer (Yang *et al*., 2018). The adhesiveness of the control (-87.20) was significantly lower than that of cake batter with 0.75% of xanthan gum (-79.58). This facilitates the control of cake batter flows easily out of the syringe feeder at 1bar pressure. The material undergoes pressure as it moves from a higher to a lower cross-sectional area and exhibits the extruder swell phenomenon as it passes through the nozzle. The degree of this phenomenon is determined by the springiness of the material supply (Anukiruthika *et al*., 2020). The ability of a substance to form a dough is explained by its cohesiveness (Wilson *et al*., 2020). Compared with all the prepared cake batter, the higher values of springiness, and cohesiveness for cake batter with 0.75% xanthan gum indicate the better strength of the material supply, making it suitable for extrusion-based printing (Wilson *et al*., 2021).

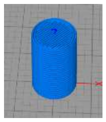
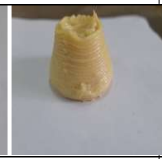
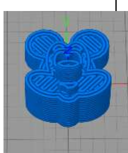
Table 2: Texture profile analysis of the material supplies.

Sample Name	Material	Hardness (g)	Adhesiveness (g.s)	Springiness	Cohesiveness	Resilience
Control	Control	87.22	-87.20	0.927	0.865	0.074
0.25% of xanthan gum	0.25%(I)	93.47	-82.64	0.948	0.874	0.072
0.75% of xanthan gum	0.75%(II)	100.21	-79.58	0.958	0.895	0.076

C. Printability and stability of the sample

The ability of a sample to be printed directly affects the stability of the 3D printed shape over time (Kim *et al*., 2017). The printed structure of different cake batters is shown in Table 3. The cake was printed in the shape of a cylinder (d = 30 mm, h = 30 mm, filling ratio = 100%) and mickey mouse (w=35mm, l=40mm, h=30mm) using a needle with a diameter (d) of 1.22mm, printing velocity of 40 mm/s and compressive pressure varied according to the different cake batter type.

Table 3: The observation and analysis of dimensions for 3D printed cake batter with two shapes i.e. cylinder and mickey mouse.

S. No.	Nozzle diameter	Model for Printing	Sample	Pressure (bar)	Top view	Side view	Diameter(d) (mm)	Height(h)(mm)	score	observation
1	1.22mm	d =30mm, h =30 mm 	Control	1			37.53	24.02	2	collapsed
2			0.25% (I)	3			33	29	4	Good molding
3			0.75%(II)	4			30.42	30	5	Good molding
4		 w =35mm, l=40mm, h=30mm.	control	1			48	20	1	collapsed
5			0.25% (I)	3			37	33	4	Good molding
6			0.75% (II)	4			35.75	30	5	Good molding

In the case of xanthan gum incorporation in 0.25% & 0.75% to the cake batter was smoothly extruded and exhibited shape retention, thus indicating a high-quality product. But an increase in xanthan gum caused the extrusion of layers to stop suddenly, which prevented the creation of a successful structure. The results obtained indicate that excess xanthan gum results in an increase in mechanical strength that is relatively substantial and leads to poor printing performance (Liu *et al*., 2019).

The control cake batter had a much smaller volume and more disorganised internal texture arrangements showed slight deformation at the top due to low material stability. The control cake batter had poor shape stability. In particular, an obscure texture and the worst printing quality were observed for the control cake batter, which almost completely lost its shape. The addition of 0.25% and 0.75% of xanthan gum to the cake batter in the group significantly altered the printing quality, according to observations. Additionally, observation of the cylinder-shaped sample revealed that the cake batter with 0.75% xanthan gum was able to maintain the cylindrical shape which was maintained at a constant volume.

The cake batter with 0.25% xanthan gum showed some deformation. The cake batter with 0.75% of xanthan gum displayed a significantly more structured internal texture compared to the other samples, as well as improved stability in both shapes.

CONCLUSION

The effects of hydrocolloid inclusion on the dimensional stability of 3D printed cake batter were examined in the current study. In this investigation, it was discovered that the rheological behaviour and textural characteristics of cake batter containing 0.75% of xanthan gum were suitable for 3D printing created objects. The results demonstrate that cake batter containing 0.75% xanthan gum could be successfully printed while maintaining its 3D design shape. Increasing the percentage of xanthan gum in the cake batter prevented the loss of its mechanical strength. The dynamic viscoelastic behaviour in the frequency sweep demonstrated that the cake batter exhibits rapid viscoelastic loss that induces deformation. In summary, this study offers a method for enhancing the shape retention of 3D printed objects and gives insight into the material qualities needed for the processing methods used in the 3D printing of food materials.

FUTURE SCOPE

The manufacturing facilities for bakeries can use the 3D food printing process to produce food in large quantities with appealing shapes. Additionally, it aids in reducing labour expenses and material loss.

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Conflict of Interest. None.

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