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Optimization of suitable post-processing method for 3D printed egg

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Abstract
3D printing of foods helps in customization of foods by adopting the concept of personalized nutrition. This work presents a study on the printability of egg fractions, focusing on optimization of various extrusion printing parameters such as nozzle height, nozzle diameter, printing speed, motor speed and extrusion rate. The printing material supply is formulated from dry fractions with 12.5% egg white powder, 54.17% egg yolk powder and 33.33% rice flour respectively, (w/w). Results showed that the addition of filler agent had a significant effect on the improvement of printability of egg. Egg could be 3D printed with fine precision and higher layer definition at 800 mm/min printing speed at 180 rpm motor speed using a 1.22 mm nozzle at 0.0123 cm^3/s extrusion rate. Two different post-processing methods (steaming and baking) were tested. The effect of post-processing of 3D printed egg was evaluated and results showed that method of cooking had significant impact in retaining shape of 3D printed samples. Based on the sensory evaluation, it was concluded that both the methods are found to be acceptable. Sensory scores were found to be higher for baked samples in terms of taste. On the other hand, steamed samples scored higher while considering retention of shape after processing. This work provides insights on the suitability of egg as a promising ingredient for personalization of diet using 3D food printing.

Keywords: 3D printing, egg, printability, post-processing, personalized nutrition

1. Introduction

3D printing is an emerging technology that helps in design and fabrication of customized foods according to the individual's preferences. Although printing on food is in practice from years ago, food 3D printing is in its infant stage which is an integration of printing and digital gastronomy (Dankar, Haddarah, Omar, Sepulcre, & Pujolà, 2018) [3]. Thus, food printing started with designing on rolls, cakes, biscuits, cookies, chocolates, pizza as toppings and so on. Now a days with the advent of new technologies and sophistication, 3D food printing is grabbing attention and possess to hold a big market in future. Various food printing technologies in practice are extrusion-based printing, selective sintering (laser or hot air), ink jet printing and binder jetting (Fuh, Hong, Zhou, Huang, & Sun, 2015) [6]. Extrusion printing is the most commonly employed technique for most of the pastes and semi-solid food materials.

With the advent of this revolutionizing technology, foods can be fabricated according to individual preferences and greatly helps in personalized nutrition. Printability refers to ability of deposited layers to withstand its own weight (Kim, Bae, & Park, 2018) [7]. Material composition and its behaviour are critical parameters in any food printing process. Several studies were reported on influence of material properties on food printability. Food materials such as chocolates, cheese, cereal-based cookies, fruits and vegetable pastes, grounded meat, food gels etc are 3D printed using extrusion-based technology (Dankar *et al*., 2018) [3]. 3D food printing is a complex process that combines printing and post processing. Based on the nature of raw material, post-processing treatments are selected. It is difficult to maintain and retain the sensorial, nutritional and stability of 3D constructs during post-processing (Lipton *et al*., 2010) [12]. Although many studies were reported on printability and material behaviour that aids in printing, only few were reported on post processing of 3D printed foods.

Different post-processing techniques employed includes boiling, steaming, frying, baking, hot-air drying and freeze drying. Commercial 3D printers are available with accessories for post-processing that combines printing followed by cooking. Foodini™ by Natural Machines works on room temperature extrusion and is being used for soft materials such as dough requires baking as post-processing operation.

Another room temperature commercial food printer in practice is BeeHex robot pizza printer developed by BeeHex; also requires baking after printing of customised pizza. Similarly, pasta printer developed by Barilla is being employed for creating innovative shapes and here boiling is applicable for cooking of 3D printed pasta. Researchers reported a study on dimensional stability during post processing of 3D printable cookie dough (Kim *et al*., 2019; Lipton *et al*., 2010) [8, 12]. Lille, Nurmela, Nordlund, Metsä-Kortelainen, & Sozer, (2018) [11] compared the effects of two different post processing treatments such as hot-air oven drying and freeze drying of 3D printed food pastes. Similarly, the changes in dimension, shape, microstructure and texture properties of cereal-based food products during microwave cooking were also reported (Severini, Azzollini, Albenzio, & Derossi, 2018) [17]. Another approach for cooking of 3D printed meat and lard by sous-vide technique was also reported (Dick, Bhandari, & Prakash, 2019) [5]. With this regard, this work aimed at analysing the printability and determining a suitable post processing technique for 3D printed egg.

2. Materials and methods

2.1 Materials

Hen eggs were procured from local market in Thanjavur, India. Rice flour was also procured from the local market. Maltodextrin (MD) (dextrose equivalent 20) was obtained from HiMedia Laboratories Pvt. Ltd. Food spices such as pepper and cumin are also procured from local market and is ground into fine powder.

2.2 Printing material supply

Egg white and egg yolk powders are obtained using refractance window drying (RWD). Drying was carried out at 45ºC and 70ºC for egg white and egg yolk separately. Around 5% of maltodextrin was added to egg yolk as filler agent that aids in collection of egg yolk powder without any loss from RWD dryer and to improve its powder characteristics. After proper drying, the RWD egg white powder (moisture of 7.588 ± 0.010 % w.b) and yolk powder (moisture of 0.449 ± 0.017% w.b) were collected and stored for further studies. Proximate analysis of collected egg powder was carried out as per AOAC standards (AOAC, 2016) [2]. Results showed that protein content of egg white and egg yolk powder were 82.817 ± 0.535% and 34.492 ± 0.589%, respectively; while, fat contents were 1.787 ± 1.250% and 39.933 ± 2.618% for egg white and egg yolk powders, respectively.

Nutritional composition of rice flour added to the material supply is: 80.58 g of carbohydrates, 8.94 g of protein, 0.48 g of fat, and 2.96 g of dietary fibre (per 100 g of flour), respectively. Rice flour taken for the study had 54.3 ± 0.23 g of starch/100 g of flour estimated by anthrone reagent method (Sadasivam & Manickam, 2008) [15]. The material supply was formulated in the following proportions of egg powder to rice flour as 1:0.5. Egg powder mixture is taken as per the total solid contents of whole egg with 11% egg white powder and 52% egg yolk powder, respectively. The printing material supply is formulated with 12.5% egg white powder, 54.17% egg yolk powder and 33.33% rice flour respectively in (w/w). The material supply was mixed with optimum amount of water and ground spices to form smooth paste without any lumps is taken for printing.

2.3 Rheology of material supply

The flow behaviour of the printing material supply was studied in rotational mode rheometer (MCR 52 series, Anton Paar Co. Ltd., Austria). Steady shear viscosities measurements are determined by ramping shear rate from 0.01 to 100 s^{-1}. Rheological data were fitted to power model (Eq.1) for analysing the relation between shear stress and shear rate (Diamante, Peressini, Simonato, & Anese, 2019) [4].

$\tau = k\,\gamma^n$ (1)

where, τ is the shear stress (Pa), γ is the shear rate (s^{-1}), k is the consistency index ($Pa.s^n$) and n is the flow behaviour index (dimensionless). As the material is subjected to different post-processing treatments, the effects of time-temperature on viscosity was evaluated by temperature ramp using Anton Paar Rheometer. The temperature was increased from 50 to 100ºC and lowered again from 100 to 50ºC over time.

2.4 3D printing process

An in-house fabricated extrusion-based delta type 3D printer was used in this study. It consists of an extrusion assembly, printing head, XYZ movement arms with stepper motor, compressor unit and syringe barrel assembly. Material supply is loaded manually into the syringe barrel assembly which in turn is connected with compressor unit. The extrusion printing process involves application of pneumatic pressure (up to 4 bar) to push the material through the nozzle. The geometry to be printed is loaded in the printing software (simplify 3D) as the input in STL format, and gets sliced into G-codes and M-codes. The gap between the printing platform and the nozzle could be adjusted manually. Micro-processor unit was used for automatic controlling of the movement of printing arms.

2.5 Post-processing treatments

Different post-processing treatments such as steaming and baking was carried out for determining the suitability of treatment for the developed 3D printed egg. Steaming is performed as per traditional cooking methods. Baking was carried out by domestic microwave oven of 2450 MHz frequency using model IFB 25BC4, India.

2.5 Physico-chemical analysis of printed samples

Colour of the post processed samples was determined using ColorFlex EZ spectrophotometer and readings were denoted using L^*, a^*, b^* colour scale. Similarly, water activity (a_w) of the post processed samples was determined using dew point water activity meter aqua lab 4TE with ± 0.001 sensitivity.

2.6 Sensory analysis

Overall acceptability of the developed post-processed 3D printed egg was analysed by a panel of twenty semi-trained panelists using 9-point hedonic scale for the following sensory attributes of appearance, colour, texture, taste, flavour, shape retention, thread precision and overall acceptability. A nine-point hedonic scale with 1 = dislike extremely, 5 = neither like nor dislike, 9 = like extremely is used.

2.7 Statistical analysis

All the analyses are carried out in triplicates and the differences among treated samples against untreated sample were analysed using one-way ANOVA with Duncan's multiple range test by SPSS software (ver. 22.0); p value < 0.05 was considered statistically significant.

3. Results and discussion

3.1 Analysis of flow behaviour

Understanding the flow and deformation of material supply is essential for evaluating the printability of the raw material.

Apparent viscosity of the material supply gets decreased with increase in shear rate due to particle disintegration when subjected to shear forces (Fig. 1). Thus, the printing material follows a pseudoplastic behaviour with n value < 1. This shear thinning behaviour is well suited for extrusion-based food printing as the material can easily flow through the nozzle head (Liu, Meng, Dai, Chen, & Zhu, 2019). Consistency coefficient k represents the structural complexity of material supply and higher value of k (13.38 ± 3.92) depicts the complex network of phosphates and lipoproteins of egg (Abbasnezhad, Hamdami, Shahedi, & Vatankhah, 2014) [1].

Pasting behaviour of the material supply is analysed in order to understand the effect of thermal treatment on material behaviour during post-processing. During the temperature cycle, viscosity keeps increasing irrespective of temperature. Pasting profiles can be expressed by peak viscosity, pasting temperature, holding strength, breakdown viscosity, final viscosity and setback viscosity. Peak viscosity represents the maximum attainable viscosity by the material supply during heating and cooling cycle. Higher peak viscosity of material supply (105.177 ± 11.489 mPa.s) was due to formation of a complex network of starch with protein and lipid matrix of egg (Saleh, 2018; Wang, Chen, Feng, Li, & Yu, 2018). Pasting temperature represents the minimum temperature at which starch gets gelatinized and gelatinization starts at 64.46 ± 3.84°C for the material supply. As the material is subjected to high temperature and mechanical stress, the corresponding breakdown viscosity was found to be 22.680 ± 4.905 mPa.s. This was due to the breakdown of polymeric chains and the effect of protein denaturation and starch gelatinization (Saleh, 2018). The holding strength and the final viscosity was found to be 82.493 ± 16.401 mPa.s and 469.433 ± 37.735 mPa.s, respectively. Setback viscosity represents amount of recovery of material during cooling and the value was found to be 386.967 ± 26.146 mPa.s.

3.2 Assessment and optimization of printing process

Printability of the formulated material supply was assessed by printing basic shapes as given in Table 1. Results showed that the formulated material supply is well suited for printing with less amount of additive (rice flour). Further, the printing conditions are optimized for range of printing process variables and the optimized conditions at 180 rpm motor speed using 1.22 mm nozzle are: 0.76 mm critical nozzle height; 800 mm/min printing speed; 0.0123 ± 0.001 cm^3/s extrusion rate. Relationship between extrusion rate and thread thickness for the formulated material supply is shown in Fig. 2. Results showed that with increasing extrusion rate, the diameter of thread gets increased linearly.

3.3 Optimization of post-processing characteristics for 3D printed egg

Common post-processing methods of steaming and baking was performed for 3D printed samples. For steaming, the temperature was raised to above 100℃ and the samples are steam cooked for about five minutes until inner core was completely cooked as per AACC method (Larrosa, Lorenzo, Zaritzky, & Califano, 2016). Similarly, baking was performed at five different power levels (20, 40, 60, 80 and 100%) for three different treatment times (2, 4 and 6 minutes) (Fig. 3). The optimized conditions for cooking of 3D printed samples are found to be 60% power level i.e. 540 W for cooking time of 4 minutes.

3.4 Effect of post processing treatments on 3D printed samples

Both steaming and microwave cooking had a significant effect on acceptability of the samples. Results of colour analysis showed that lightness (L*) and redness (a*) values were higher for microwave cooked samples than steamed one (Table.2). Addition of rice flour had a significant effect on whiteness of material supply (Matos & Rosell, 2013) [14]. On the other hand, yellowness value is higher for steamed samples than microwave cooked samples. This was due to stability of carotenoid pigments of egg yolk during steaming than microwave cooking (Lee, Kim, & Han, 2018) [7]. The effect of post-processing treatments on dimensional stability of 3D printed samples (Fig. 4). Both steaming and microwave cooking employs heat for cooking of foods at different extents. From sensory analysis, steaming results in harder texture due to starch gelatinization while microwave cooking resulted in fluffy texture. This is due to sudden release of moisture from food matrix that results in volume expansion of microwave cooked samples (Solanki, Mridula, & Nanda, 2018) [18]. This can be evident from lower a_w of microwaved samples (Table 2).

Further, the results of sensory analysis showed that 3D printed samples are mostly preferred than non-3D printed ones (Fig. 5). Overall acceptability of both steamed and baked 3D printed samples are nearly equal. Since, steamed 3D printed samples scored higher in retaining shape with less deformation after post-processing whilst baked 3D printed samples scored higher in terms of taste preference. Thus, the study reveals that both steaming and baking are well suited for post-processing of 3D printed egg.

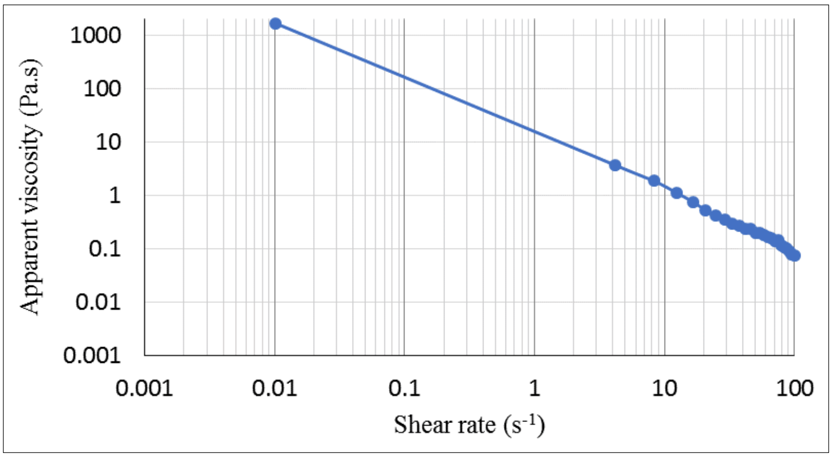
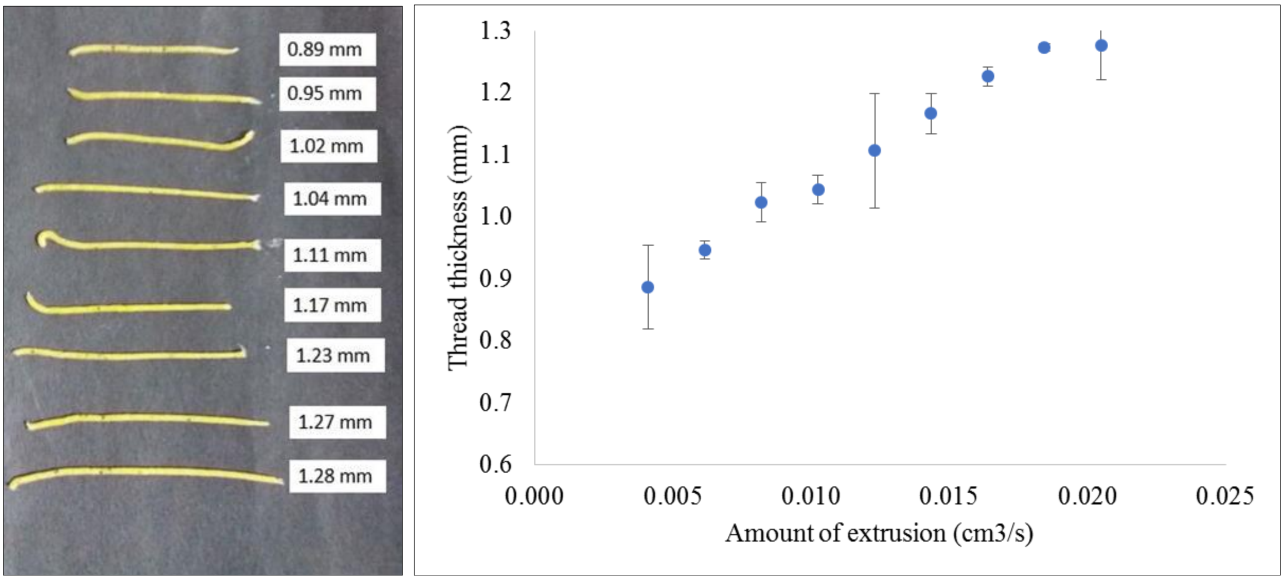


Fig 1: Apparent viscosity curve for formulated whole egg material supply



a **b**

a) Illustration of thread thickness (images are not to the scale); b) Relationship between extrusion rate and thread thickness

Fig 2: Optimization of extrusion rate for formulated whole egg material supply

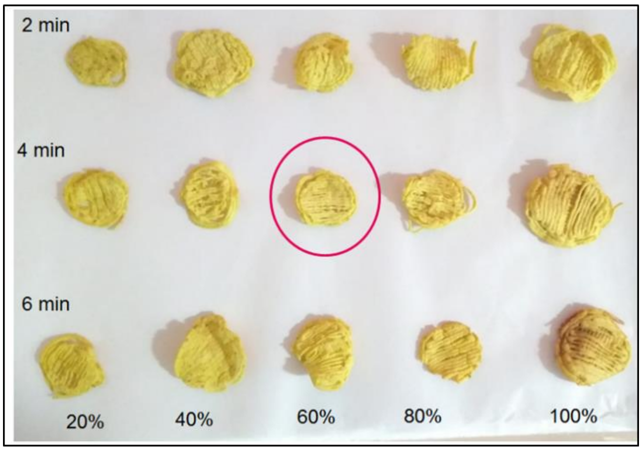


Fig 3: Optimization of power levels and time during microwave cooking

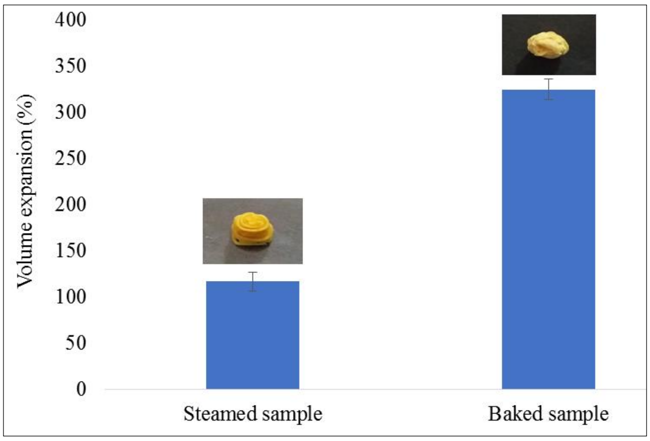


Fig 4: Volume expansion of post-processed 3D printed samples

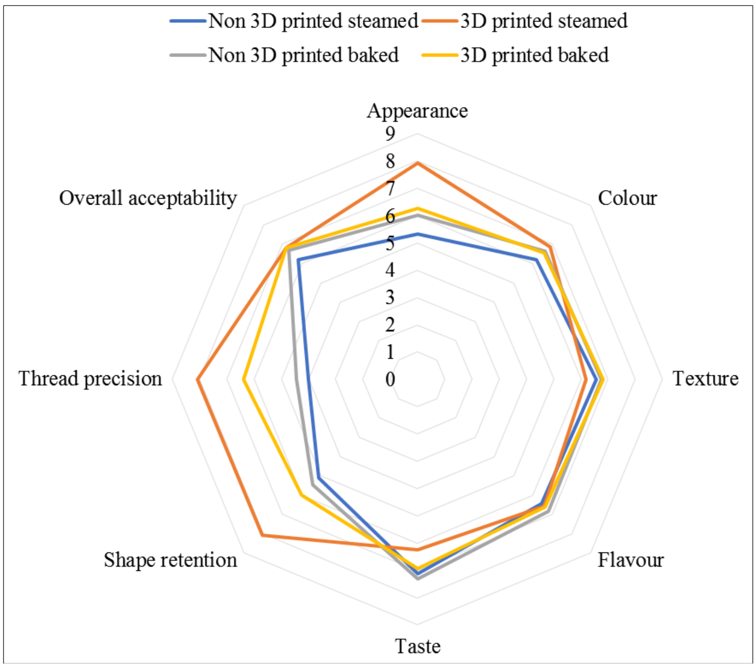


Fig 5: Sensory analysis of post-processed samples

Table 1: Printability test for formulated whole egg material supply

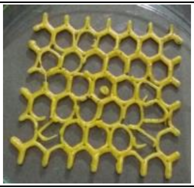
Printability test		
One-dimensional test	**Two-dimensional test**	**Three-dimensional test**
		
Line test	Lattice test	Cylinder test

Table 2: Colour analysis and water activity of post-processed samples

Treatment	Colour scale				Water activity (a_w)
	L*	***a****	***b****	***ΔE***	
Untreated sample	59.10 ± 0.08^b	14.89 ± 0.04^c	53.22 ± 0.19^c	-	0.969 ± 0.001^b
Steam cooked sample	56.69 ± 0.15^a	6.87 ± 0.04^a	38.15 ± 0.20^b	17.24	0.943 ± 0.003^b
Microwave cooked sample	69.41 ± 0.25^c	8.29 ± 0.11^b	36.06 ± 1.13^a	21.07	0.389 ± 0.024^a

Data are presented as mean values ± SD (n=3) and lowercase superscripted letter in same column means significantly different between various material supply ($p<0.05$).

4. Conclusion

This study presented an in-depth analysis of suitable post-processing methods suitable for 3D printed egg. Final optimised printing conditions for material supply was found to be of 800 mm/min printing speed at 180 rpm motor speed using a 1.22 mm nozzle with 0.0123 cm^3/s extrusion rate. The optimized conditions for post-processing of 3D printed egg was found to be: cooking time of five minutes, cooking temperature of more than 100℃ and baking power level of 450 W for steaming and baking, respectively. Both steaming and boiling was found to be acceptable with a small deviation in taste and shape retention. Steamed samples retained its shape possessing a tough texture due to the effect of rice flour and elastic nature of yolk. On the other hand, microwave cooked samples were lighter in weight and expanded due to rapid evaporation of water from material supply. Thus, this study explored the potential applications of 3D printing in development of newer egg product with desired sensory attributes. Further, the study can be utilized for formulation of personalised diet using 3D printing.

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