# 3D food printing as a promising tool for food fabrication: 3D printing of chocolate

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Abstract

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The optimisation of printing dark chocolate was investigated, which included 3D printer modification. The modification comprises development of custom printer bed an inbuilt water recirculation system with a slow flow rate of 6.3 mL/s to avoid vibration. Additionally, a fan was attached to enhance the solidification of chocolate. It was found that 32°C was the optimal condition of chocolate melting and this temperature was applied in the printing process. The addition of the support structure on the mechanical properties of chocolate such as cross and parallel support structures printed in a hexagonal shape was also investigated. Findings indicated that the cross support increased the stability and strength (57.5 $\pm$ 4.8 N) of chocolate more than the chocolate printed with parallel support  $(50.5\pm2.7 \text{ N})$  and without any support structure  $(12.6\pm6.1 \text{ N})$ . Different infill structures (infill pattern and percentage) can contribute to the textural modification of 3D printed chocolate. The appearance of the 3DP construction was vital as this modality can influence the acceptability of the product. Sensory analysis was conducted among 30 semi -trained panellists. Most participants favoured the appearance of sample 3DP100% IP (1.33) to those of samples 3DP25% IP (2.00) and 3DP50% IP (2.67). On the textural perspectives, consumers indicated their potential preferences on chocolate printed with 25% infill percentage. Similar results from consumer paired-preference test were obtained. These results suggested that consumer realised the potential of 3D printing for textural modification.

# 1. Introduction

3D printing is a layer-by-layer three-dimensional building process (Wegrzyn *et al.*, 2012). The process operates in a similar way to printing on a paper from a word processor program on a personal computer, except that it is in 3D. That is to say, in 2D printing, the image or text is printed row by row until it is complete across a length and width in a single layer (or a few layers in bold font function). However, the process of 3D food printing involves food-grade products such as sugar, starches, or protein to create an edible printed food (Zimmerman *et al.*, 2012; van der Linden, 2015). In essence, printing food is done through the careful layering of tiny or thin semi-liquid food particles on top of each other to create a 3-dimensional novel processed food (Lam *et al.*, 2002).

The early concept of 3D printing (3DP) was rapid prototyping (RP), the process of modelling, assembling

and fabrication via computer-aided design (CAD) which was developed by Kodama from Japan in the late 1980s (3D Printing Industry, 2014). RP technology evolved into Additive Manufacturing (AM) which is a more advanced form that can construct intricate 3D objects layer-by-layer, either by using plastic polymer filaments, metal and, more recently, edible materials such as sugar and chocolate (Sher and Tutó, 2015). 3D printing has begun to emerge in food production and 3D food printers have been designed specifically for food fabrication. According to Gibson et al. (2010) apart from RP, there are some broadly used technologies in AM which are stereolithography (SL), FDM and selective laser sintering (SLS). According to Sun et al. (2015) there are a number of research studies and projects in 3D food printing in many areas which range from the development of conceptual ideas to an in-depth understanding of material properties.

Chocolate is a complex composition that contains cocoa solids, milk solids, sucrose and lecithin. Altogether, these ingredients influence the rheological properties which are an important parameter for determining the printability of chocolate. The most important component in chocolate is the complex crystal structure of fat. There are six crystal polymorphs existing in chocolate (Afoakwa, 2010). These crystals have different ranges of melting points from 16.1°C up to 36.8 °C (Talbot, 2009). However, the most favourable crystal that gives chocolate its quality attributes such as smoothness, a glossy look and snap ability is Form V ( $\beta$ ) with a melting point of 33.8°C (Afoakwa, 2010). The solidification temperature (usually the same as the melting temperature of the  $\beta$ -crystal type) is an important material property that determines the feasibility of layerby-layer printing. The printed layer needs to quickly solidify to hold the subsequent printed layer. Therefore, having a cool printer bed is particularly important in the 3D printing of food materials such as chocolate.

Some of the 3D printers that are available in the market are not equipped with a cooling bed system. However, for substances like chocolate, to maintain the bed temperature, a cooling system such as cold water circulation is needed to ensure the printer bed will remain cool. It should be noted that a cold bed temperature can also lead to condensation of moisture on the bed because the surrounding air may reach the dew point temperature when it hits the cold bed. Thus, to avoid moisture condensation, it is also important that there is sufficient airflow around the printer bed.

Altering structural properties in designing food to modify the textural properties such as infill structure is relatively new in the 3D food printing field. There were reports on designing internal structure of 3D constructs in order to modify the textural properties of the printed foods. Liu et al. (2018) investigated the textural and structural quality of mashed potato (soft material) by modifying infill percentage (10%, 40%, 70% and 100%) with different infill patterns (rectilinear, honeycomb and Hilbert curve) and variation in shell perimeters (3, 5 and 7 shells). They reported that firmness values 25.15 g to 144.81 g and Young modulus (487.99 Pa to 43,306.50 Pa) increased and solely affected by variation in infill density between 10% and 70%. This indicates that an increase in infill percentage will increase the mechanical strength (firmness and Young modulus) of the 3D printed mashed potato. Severini et al. (2016) reported that the addition of an inner support structure (cross and parallel) was essential to hold the 3D printed cerealbased product for post-processing to make the constructs more stable. In this case, the infill structure was mainly designed to aid the stability of the construct.

Recently, the acceptance of 3D printed food has been studied in various settings and among targeted consumers. Brunner et al. (2018) explored Swiss consumers' attitudes and attitudinal changes toward 3D printed food using a survey. The questionnaire was constructed with 14 predictors, constituting variables of food neophobia, benefits perception, nutritional knowledge, previous knowledge technology and neophobia (Brunner et al., 2018). After an intervention which consisted of the feedback from the respondents, they reported that its outcome was successful in overcoming consumers' food neophobia and convincing consumers that 3DFP technology is capable of producing healthy and individualised meals with exciting food design. Although the advantages and numerous possible uses of 3D food printing are already widely discussed (Sun et al., 2015; Izdebska and Zolek-Tryznowska, 2016; Godoi et al., 2016; Mantihal et al., 2019), very little research has been conducted on consumers' attitudes, perceptions and acceptances toward food produced by 3D printing Therefore, this study aimed to demonstrate the capability of 3DFP to modify food texture by altering the internal structures of printed chocolate. A sensory evaluation of texture-modified 3D printed chocolate was conducted among 30 semi-trained respondents to assess consumers' preferences concerning sensory attributes such as texture and appearance and their overall preferences.

# 2. Materials and methods

#### 2.1 Materials

Two types of dark chocolates, Cadbury dark chocolate (Choc-1) and Callebaut dark chocolate buttons (Choc-2) purchased locally in Brisbane, Australia was used in this study. Choc-1 was also used for cast chocolate samples as a control. The composition of the Cadbury dark chocolate was 53% (minimum) cocoa solids, 35% (minimum) cocoa butter, 0.5% lecithin and approximately 11.5% sugar. The Callebaut dark chocolate buttons (bittersweet flavour, Lindt Piccoli) were composed of 58% (minimum) cocoa solids, 33% (minimum) cocoa butter, 5% anhydrous milk fat, 0.5% lecithin and vanilla and about 3.6% sugar. Both dark chocolate samples (Choc-1 and Choc-2) were ground separately into powder in a controlled temperature room at around ~ 5°C and kept in refrigeration (~8°C) separately until the initiation of the printing process.

# 2.2 Commercial dark chocolate casting process

Casting of Choc-1 was done to compare it with the textural property of 3D printed chocolate. Before casting, the chocolate was melted at a controlled temperature at around 32°C using a chocolate melting machine

(ChocEdge, UK). Melted chocolate samples (10 g) were poured into a 3D printed cast (printed using Acrylonitrile butadiene styrene (ABS) filament (Figure 1)) and covered by a thin layer of clear food grade plastic wrap. All samples were kept under refrigeration at around 8°C until the initiation of the textural analysis and sensorial evaluation.



Figure 1. The 3D cast printed using Da Vinci 2.0 dual nozzle model XYZ printer with ABS filament.

#### 2.3 Printing process

The 3D chocolate printing consisted of three essential steps: (i) making the 3D geometry design, (ii) slicing the design and (iii) the printing process.

#### 2.3.1 3D geometry design

Chocolate Model (1) of 20 mm x 50 mm and 5 mm thickness and Chocolate Model (2) of 43.5 mm x 35.5 mm and 5 mm thickness were designed (Figure 2) and the Hexagon design consist of 20.0 mm height and 20.0mm width design with support structure Cross and parallel (Figure 3) using TinkerCad online software.



Figure 2. 3D model designs of rectangular shape (a) Model -1 (20 mm x 50 mm and 5 mm thickness) with Honeycomb pattern in variation of infill density of 25%\_IP, 50%\_IP and 100%\_IP (b) Model-2 (43.5 mm x 35.5 mm and 5 mm thickness) in rectilinear pattern with 100%\_IP. IP refers to infill percentage.



Figure 3. 3D model design of hexagonal model with (a) cross support (b) parallel support (c) no support.

# 2.3.2 Slicing

The 3D models from the above online software were uploaded into the Repetier-Host software (.stl file) and sliced using Sli3er configuration to generate the g-code for each model. The shell perimeters were set at default three shells (approximately ~2.34 mm thickness) considering the inner nozzle diameter is 0.78 mm. Figure 2 illustrates the 3D chocolate samples design for sensory analysis Model (1) for Choc-2 was set to a honeycomb infill pattern with a variation of infill of 25%, 50% and 100% as shown in Figure 2. Model (2) for Choc-1 was set to a rectilinear pattern with 100% infill to mimic the commercial chocolate block. Figure 3 represent the design models of hexagon shape custom with internal supports, cross, parallel and no support for mechanical strength analysis. All samples were sliced (with the specific g-code extracted for each 3D model) according to each infill pattern and infill percentage using Sli3er software.

#### 2.4 Operational conditions

Porimy 3D chocolate printer (Porimy Co. Ltd, Kunshan, China) was used in this study. Prior printing, the extruder temperature was set at 32°C for 5 mins to ensure extruding temperature are controlled and maintained. Printing parameters were set as follow: printing speed 70 mm/s, extrusion temperature calibrated at 32°C, nozzle size 1.5 mm (inner diameter 0.8 mm) and printer bed temperature maintained at 15°C to 22°C. These parameters were set based on correlations between thermal and flow behavior of the chocolate (Mantihal et al., 2017). Figure 4 illustrates the schematic diagram of the 3D printing mechanism which uses a rotary screw extrusion method to extrude chocolate. This printer automatically regulates the proper gap between nozzle and printer bed by means of a built-in Reprap XYZ system (a 3D printing system that navigates printer movement). The printed samples were stored in refrigeration at around 15°C until quality assessment



Figure 4. Schematic diagram of Porimy 3D chocolate printer and its printing mechanism.

analysis.

# 2.5 Dimensional and weight measurement of 3D printed chocolates

A digital calliper (0-150 mm, CraftRight®, Bunnings, Australia) was used to measure the dimensions of the 3D printed chocolate (length, width and thickness). This was done in three different positions on each printed chocolate samples for accuracy and the average value (mm) was reported. Also, a digital weighing balance was used to assess the weight of each printed chocolate sample.

### 2.6 Texture properties of 3D printed chocolate

The texture attribute of hardness was obtained by texture analysis using a texture analyser (Model TA-XT Plus, Stable Microsystem, UK) equipped with a 10.0 kg load cell with Exponent version 6.1.9.0 software. A TA-42 knife blade was used and the test was conducted at room temperature (around 23°C). Compression mode was used to analyse the samples at 10 mm distance. A pre-test of the speed of 1.0 mm/s and the test speed of 2.0 mm/s with 5.0 g trigger force were applied. The measurement was conducted in triplicate and the data of maximum force (N) from the force-displacement curve were extracted.

### 2.7 Sensory evaluation

The sensory profile of the printed chocolate was carried out to determine consumer acceptability of 3D printed chocolate. The chocolate was evaluated using a ranking test for preferences and a paired-preferences test with the aid of RedJade sensory evaluation software. The sensory test was conducted in a sensory analysis laboratory, at the School of Agriculture and Food Sciences (SAFS), the University of Queensland, Australia. Ethical clearance approval for this evaluation was granted by the Human Research Ethics Committee, University of Queensland. 30 semi-trained (panellist who familiar with chocolate testing) panellists composed of 21 females and nine males from the School were involved in the sensory test. The age range of the panellists was between 28 and 55 years. The printing time for each sample ranged from 3 to 5 mins, depending upon the sample's infill percentage. The chocolate samples were kept at room temperature (23°C) before evaluation. Two sets of samples were served to the panellists, starting with three samples for a ranking test for preferences. Once the panel completed the ranking test, the second set of samples (2 samples) for the paired preference test was given to the panellists.

For the ranking test for preferences, three dark chocolate (Choc-2) samples were prepared with

dimensions of 20 mm x 50 mm and 5 mm thickness, printed in honeycomb infill pattern with infill percentages of 25%, 50% and 100%. The sensory attributes assessed were appearance, hardness and overall preferences using Rank 1 for the most preferred, Rank 2 for the medium ranking and Rank 3 for the least preferred. The printed samples were coded with three random numerical numbers and placed in random order on one paper plate for each respondent. For the pairedpreferences test, two dark chocolate (Choc-2) samples were served (dimensions: 43.5 mm x 35.5 mm and 5 mm thickness). One sample was printed in 100% infill with a rectilinear pattern and another was the cast chocolate block. The samples were coded with three random digits and served randomly on the plate. In this test, the panellist had to choose which chocolate they preferred the most.

### 2.8 Statistical analysis

Dimensional properties (weight, width, length and thickness) and mechanical strength (Force -N) were presented as mean values  $\pm$  standard deviation. Minitab version 17 (statistical software) was used to analyse the significant difference between values using the one-way analysis of variance (ANOVA) Tukey's test (where applicable). The significant difference was determined at *p*-value (*p*) of less than 0.05. The ranking of preferences (sensory analysis) was compared using a nonparametric, Friedman test.

## 3. Results and discussion

# 3.1 Modification of printer bed and development of cold water circulation system

A square (200 mm x 200 mm x 10 mm) stainless steel printer bed was designed to address the solidification issue of chocolate. The first layer of extrusion supports any subsequent layers as the printer builds up the structure. The printer bed was designed with inner water circulation to allow faster solidification of the extruded chocolate, by maintaining the bed temperature ~16°C. In addition, the temperature of the printer bed can also be set even cooler by circulating colder water. Figure 5 illustrates the cooling printer bed.



Figure 5. Cooling printer bed made in this study. The recirculation tubes (diameter 0.8 cm total 80 cm length) are enclosed as heat exchanger inside the plate.

In order to cool the printer bed, a customized cold water circulation system was developed. Coldwater flowed at low pressure with a 12W water pump to reduce the vibration on the bed during printing. It was designed with a water inlet and outlet for water inflow and outflow via an 8 mm diameter silicon tube. Figure 6 shows the cold water circulation system.



Figure 6. Schematic diagram of water circulation system with a 12W submerged pump.

The volumetric flow rate was calculated using the formula: Q = V/t where Q is volumetric flow rate, V is volume in mL and t (time) is in seconds. An average volume (mL) of 380 mL was collected in the volumetric flask in 60 seconds. The flow rate (Q) was thus 6.33 mL/s. A low flow rate of cold water is important in this study to avoid vibration during water circulation as this may interrupt the chocolate printing process. The printer bed temperature was measured as ~16°C during the printing process. Ice was added after every 30 mins of printing time to ensure the printer bed maintained the required temperature. The complete modified 3D printer is depicted in Figure 7.



Figure 7. 3D chocolate printing system with additional feature (a) water circulation system (b) custom printer bed.

# 3.2 Printer bed stabiliser (support)

The acrylic printer bed of the Porimy 3D printer is a stainless steel bed. Hence new supports were devised to stabilize the bed. Four printer bed stabilizers (Figure 8) were developed through 3D design and printed using XYZ printing via a Da Vinci 2.0 filament 3D printer. A square block with 38 mm x 34 mm x 4mm (medium infill 25%) was printed with ABS filament with 7 mm diameter hole at the centre for ease of attachment on the

printer. It was observed that the custom printer bed stabilizer was able to support the stainless steel printer bed.



Figure 8. Printer bed support printed using 3D filament printer (XYZ printing) with ABS filament.

#### 3.3 Addition of air blowing fan

During the printing process, the air was blown toward the deposited chocolate using a fan, which assisted in speeding up the solidification process as the 3D construction's height is built. Each layer needed to solidify quickly to support the upcoming layer to avoid the structure from collapsing. In addition, air from the fan also helped to reduce the condensation on top of the printer bed as water droplet formation may occur while the printer bed is cooled depending on the temperature used and the humidity of the ambient air. Figure 9 shows the fan (USB Fan 2.25 W) attached to the printer. Airflow rate was not measured.



Figure 9. Attachment of USB fan (2.25 W) on the 3D Porimy printer.

#### 3.4 Optimization of nozzle height

Nozzle height is defined as the gap between the nozzle tip and deposited top layer on the printer bed. Attalla *et al.* (2016) reported that the nozzle distance



Figure 10. Schematic illustration of effect of distance between nozzle tip and printer bed [unit measurement for diameter in mm, nozzle size 0.78 mm, printing speed 70 mm/s, printer bed temperature  $\sim 16^{\circ}$ C and nozzle height (a) 0.5 mm (b) 1.0 mm (c) 0.78 mm].

could influence the geometry shape of a 3D printed product. Theoretically, the extrusion mass flow rate and the movement speed of the nozzle assumed to directly influence the nozzle height and would result in a bed of extruded material with a diameter equal to that of the nozzle (Khalil and Sun 2007). Ideally, the extruded chocolate should have the same diameter as the nozzle size considering no swelling, shrinking or expansion of the extruded material (Yang et al., 2018). Many trials were done in this study to determine the accurate nozzle height suitable for chocolate extrusion. In this experiment, a small nozzle with an inner diameter 0.78 mm were used. Periard et al. (2007) suggested that a small nozzle diameter helps to construct a fine resolution and a smooth 3D object. Three extruded first layers with varied nozzle height settings are shown in Figure 10.

A thicker extruded line (diameter 0.98 min - 1.90 max) than anticipated was obtained with a nozzle height 0.5 mm as shown in Figure 10(a). A broken extruded line (diameter 0.92 min - 1.21 max) can be seen in Figure 10 (b) where the nozzle height was 1.0 mm. The best extruded line (diameter 0.74 min – 0.79 max) considered to be almost equivalent with nozzle diameter size was observed in Figure 10(c) where the nozzle height was 0.78 mm. Thus, we found that in chocolate extrusion, it was best that the nozzle height is the same as the nozzle diameter. This result was similar to that in a previous study (Yang *et al.*, 2018).

# 3.5 Mechanical strength of 3D constructs as a function of support structure

Snap quality is an important quality parameter of chocolate produce. The influence of supports on the snap force was determined using a texture analyser. In this experiment, only callebaut dark chocolate (Choc-2) were printed. Table 1 shows the mean value of force (N) needed to break each sample. The force required to break the chocolate samples (based on diameter) were

significantly different (p < 0.05). It was observed that the constructs with the cross support required a higher force to break the sample with >56.00 N and had a high snap quality and firmer texture as compared to other sample designs. Sample with no support required less force to break the sample with a force of <16.0 N. Cross support structure enabled to hold the main angle of the chocolate geometry (Figure 11) keeping it firm and stable as compared to sample with parallel support and without support.

Table 1. Mean value of Force (N) required to break chocolate sample according to the type of support.

		Force (N)	
Supports	(diameter 43.0 mm)	(diameter 53.0 mm)	(diameter 63.0 mm)
Cross Support	56.91±7.4ª	57.48±4.8 <sup>a</sup>	58.42±4.4 <sup>a</sup>
Parallel Support	$50.01{\pm}6.4^{a}$	$44.68{\pm}10.7^{a}$	$50.52{\pm}2.7^{a}$
No support	11.63±3.1 <sup>b</sup>	$12.61 \pm 2.5^{b}$	$15.84{\pm}5.0^{b}$

Values with different superscripts in the same row are significantly different at p < 0.05.



Figure 11. Three model designs of printed 3D chocolates (a) hexagonal shape with cross-support (b) hexagonal shape with parallel support (c) hexagonal shape with no support.

Figure 12a, 12b and 12c illustrate steep curves with a short displacement indicating a good snap quality. However, a sample with diameter 43.0 mm (without support) in Figure 12c experienced a long and slow escalation signifying less snap quality and only small force (11.63 N) needed to snap the sample. The mechanical strength of commercial dark chocolate is significantly affected by the content of cocoa solid particles as reported by Nedomova *et al.* (2013). They

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reported that force (N) required to break dark chocolate (70% cocoa solid content) was 40.0 N at crosshead speed 1 mm/min. In this study, cocoa solid content in the samples was constant (58%) and the chocolate was printed with varied support structure and diameter. These variables also affected the mechanical strength of 3D printed dark chocolate. Beckett (2008) reported that a steep curve of maximum force and short displacement related to a good snap quality of chocolate. The addition of support structure has not only improved the snap property but also increased the stability printed product. This is important in designing complex 3D constructs, specifically creating higher constructs. Supports aid to hold and maintain the pre-determined shape. The ultimate aim of support structure is to stabilise the intricate structure and also to develop the texture of the food. Depending on the textural properties aimed, the number of support structure can be varied. Internal structures with different level of thickness and numbers on the textural properties of chocolate will be the subject of future studies. A comparison was carried out among three internal structure designs: (1) void space, (2) built parallel support and (3) built cross support. The arrangement of support structure whether parallel or cross support also determines the mechanical strength of 3DP object. It was demonstrated that cross support resulted in more stable 3D construct as per the higher force required to break the object during snap tests.

#### 3.6 3D printed chocolate for sensory evaluation

The 3D printed constructions and cast chocolate block for Choc-1 (Cadbury dark chocolate) and Choc-2 (Callebaut dark chocolate) are illustrated in Figure 13. As can be seen in the figure, the 3D printed chocolate constructed with various infill percentages (25%, 50% and 100%) were able to support the size and shape of the constructions. Also, the hollow structure was visible in chocolate printed in 25% and 50% infill when the chocolate was snapped. The textural and preferences of 3D printed chocolate are discussed in the subsequent section.



Figure 13. Representative images of 3D printed and cast chocolate samples – target geometry as reference. (a) Choc-1 is Cadbury dark chocolate – one sample was printed in 100% infill with rectilinear infill pattern and the other is a cast sample. (b) Choc-2 is the Callebaut dark chocolate printed in various infill percentages, 25%, 50% and 100%, with a honeycomb infill pattern. IP means infill percentage.

# 3.7 Evaluation of dimensional properties and weight of 3D printed chocolate

Table 2 shows the recorded thickness, width and length of the 3D constructs. As can be seen in Table 2, the thickness of the construction printed with Choc-2 (regardless of infill percentages) remained the same; there was no significant difference (p < 0.05) between samples printed in 25% (5.09±0.03 mm), 50%  $(5.12 \pm 0.07)$ mm) and 100%  $(5.06 \pm 0.04)$ mm). respectively. Also, the width and length of the constructions showed similarity to that of the predesign geometry, as there was no significant difference (p < p0.05) between samples printed in 25%, 50% and 100% infills. Similarly, for samples printed with Cadbury dark chocolate (Choc-1), the thickness, width and length of the printed product (100% infill) were not significantly



Figure 12. Force-distance curves measured by texture analyser of 3D printed chocolate with (a) cross support (b) parallel support (c) no support using break probe with a test speed 2.0 mm/s.

Table 2. Recorded dimensional properties (thickness, width, length) and weight of 3D printed Choc-1 with 100% infill (rectilinear pattern) and cast samples and Choc-2 samples with infill of 25%, 50% and 100% (honeycomb pattern).

Dimension		Cho	Choc-1		Choc-2		
		100%_IP	Cast	25%_IP	50%_IP	100%_IP	
Thickness	(mm)	$5.07{\pm}0.02^{a}$	$5.00{\pm}0.0^{a}$	$5.09{\pm}0.03^{a}$	$5.12{\pm}0.07^{a}$	$5.06{\pm}0.04^{a}$	
Width	(mm)	$35.34{\pm}0.52^a$	$35.50{\pm}0.0^{a}$	$20.44{\pm}0.51^{a}$	$20.40{\pm}0.53^{a}$	$20.09{\pm}0.03^{a}$	
Length	(mm)	43.75±0.21 <sup>a</sup>	$43.50{\pm}0.0^{a}$	$51.15{\pm}1.02^{a}$	$50.06{\pm}0.09^{a}$	$50.08{\pm}0.07^{a}$	
Weight	(g)	$9.21{\pm}0.52^{b}$	$10.00{\pm}0.0^{a}$	$4.70 \pm 0.64^{\circ}$	$6.03{\pm}0.21^{b}$	$8.39{\pm}0.65^{a}$	

Values with different superscripts in the same row are significantly different at p < 0.05. IP, infill percentage.

different (p < 0.05) with those of the cast chocolate block (see Table 2).

The dimensions of the cast chocolate block remain as per the predesign model because the chocolate was moulded explicitly to the predetermined dimensions. Similar results were reported by different authors for other 3D printed materials. Liu et al. (2018) reported that mashed potato constructions printed in 10%, 40% and 70% infill were closely matched to the design geometry. Also, Yang et al. (2018) designed an intricate geometry of Mickey Mouse with a predesign model (length 5.40 cm, width 5.00 cm and height 2.30 cm) using dough as the main substrate. They verified that 3D printing was able to re-create an intricate design precisely to that of the design geometry with the dimensions of 5.41 cm in length, 4.95 cm in width and 2.28 cm in height. These findings indicate that 3D food printing was capable of producing a product with accurate dimensions. Thus, the results suggest that this novel technology is a great tool for food customisation.

A significant difference (p < 0.05) was observed in the weight of each construction printed in various infill percentages: 25% (4.70±0.64 g), 50% (6.03±0.21 g) and 100% (8.39±0.65 g). Also, the weight of printed chocolate (Choc-1) was recorded as less than that of the cast chocolate block (9.21±0.52 g). The difference of weight between the 3D printed chocolate and cast samples is due to the layer-by-layer deposition method in the 3D printing process. In the printing process, the fusion between layers of chocolate will be formed by gravity, cohesive effects and the swell behaviour of extruded chocolate (Mantihal et al., 2019). Incomplete fusion of layers with their adjacent layers will cause micro-voids in the microstructure. These layers could be visually seen in the 3D printed chocolate. In comparison, the cast sample preparation involves filling the mould with molten chocolate to form a single solid and compact mass. Therefore, this difference in production influences the weight of the chocolate.

It is expected that increasing the infill percentage will increase the weight of the printed construction (Table 2). The increased weight is due to the amount of extruded material used to fill the construction to accommodate the preset infills (Severini *et al.*, 2016). Fernandez *et al.* (2016) also reported that the weight of the constructs (ABS filament) significantly increased from 11.2 g up to 18.9 g, respectively as the constructs were printed from 20% to 100% infill (with honeycomb infill pattern). These results confirm that a variation in infill percentage would strongly influence the 3D food construction's weight.

# 3.8 Textural evaluation of 3D printed and cast chocolate

In this experiment, honeycomb infill pattern was applied as this criss-cross pattern provides strong support in 3D construction (Murphy and Atala, 2014; McLouth *et al.*, 2017). Figure 14 exhibits of force (N) as a function of distance (mm) of chocolate printed with Choc-1 (with 100% infill and cast samples) and Choc-2 with a variation of infill percentages (25%, 50% and 100%). Figure 14a clearly shows that the cast chocolate requires a higher force (N) to break the samples than that of the 3D printed construction with 100% infill. In Figure 14b, a variation of force (N) was observed as the infill percentage increased. A steep curve with slight displacement can be seen indicating a good snap quality of all the chocolate samples (Beckett, 2011; Mantihal *et al.*, 2018).



Figure 14. Representative graphs of force (N) as a function of distance (mm) of 3DP chocolate printed and cast for samples (a) Choc-1 with 100% infill for 3DP (rectilinear pattern) and (b) Choc-2 samples various infill percentages of 25%, 60% and 100% (honeycomb pattern) with a pre-test speed of 1.0 mm/s and test speed 2.0 mm/s with 5.0g of trigger load of all chocolate.

Table 3 summarises the force (N) required to break chocolate samples printed with Choc-1 (with 100% infill in a rectilinear pattern and cast samples) and Choc-2 (in 25%, 50% and 100% infill) in a honeycomb pattern. As

Table 3. Recorded force (N) to break the chocolate samples with various infill percentages (25%, 50% and 100%) and cast samples.

	Choc-1		Choc-2		
	100%_IP	Cast	25%_IP	50%_IP	100%_IP
Force (N)	71.06±1.35 <sup>b</sup>	$83.58{\pm}1.40^{a}$	$20.44 \pm 1.12^{\circ}$	$33.52 \pm 1.55^{b}$	$54.43{\pm}1.47^{\rm a}$

Values with different superscripts in the same row are significantly different at p < 0.05.

3.9 Sensory profile of 3D printed chocolate

The sensory profile of the printed chocolate was

carried out to determine consumer acceptability of 3D

printed chocolate. Two sets of samples were served to

the panellists, starting with three samples for a ranking

test for preferences. Once the panel completed the

ranking test, the second set of samples (2 samples) for the paired preference test was given to the panellists. For

the ranking test for preferences, three dark chocolate

(Choc-2) samples were prepared with dimensions of 20

mm x 50 mm and 5 mm thickness, printed in honeycomb

infill pattern with infill percentages of 25%, 50% and

100%. The sensory attributes assessed were appearance,

hardness and overall preferences using Rank 1 for the

most preferred, Rank 2 for the medium ranking and Rank

3 for the least preferred. The printed samples were coded

with three random numerical numbers and placed in

random order on one paper plate for each respondent.

For the paired-preferences test, two dark chocolate (Choc

can be seen in Table 3, the 3D printed Choc-2 required an increase in the force (N) to break the samples as the infill percentage increased. It was observed that chocolate printed with 25% infill required 20.44±1.12 N, 50% required 33.52±1.55 N and 100%, 54.43±1.47 N, respectively. The forces were significantly different at p< 0.05.

For Choc-1, there was also a significant difference (p < 0.05) in the force (N) required to break the cast and 100% infill chocolate samples,  $83.58\pm1.40$  N and 71.06±1.35 N, respectively. The reduced resistance to break the printed Choc-1 (3DP100%\_IP) is due to a weak interface of layers affected by the sequential layering upon printing. This result is also in line with Le Tohic *et al.* (2018) who reported that the hardness of the 3D cheese construction diminished by ~ 49% compared to that of cast cheese. Therefore, cast samples are relatively tougher than printed constructions even when printed at 100% infill.

Also, an increase in percentage infill means that the intensity of deposited layers (mesostructure) becomes compact as the higher IP is achieved (Rankouhi et al., 2016). Figure 13 illustrates that a larger hollow structure can be seen in samples printed with 25% infills and this becomes compact when samples are printed in 50% infill while no void was visible for samples printed in 100% infill. A similar concept was presented in a pectin-based food stimulant printed in honeycomb structure (Vancauwenberghe et al., 2018). The researchers reported that Young's modulus of printed samples with larger cell size was less (11.58±1.43 kPa) than that of samples printed in a cube which was similar to printing in 100% infill (118.58±12.10 kPa). Thus, by altering the infill percentage the texture of the printed construction will substantively change.

Based on the results of the textural properties testing of the 3D printed chocolate, we found an increase in the mechanical strength of 3D printed chocolate is correspondingly influenced by the variation of infill percentage. Overall, the texture (hardness) of 3D printed chocolate can be changed subject to internal structure modification. In the next section, we attempt to explore the sensorial properties of 3D printed dark chocolate through sensory evaluation and assessing consumer preferences. -2) samples were served (dimensions: 43.5 mm x 35.5 mm and 5 mm thickness). One sample was printed in 100% infill with a rectilinear pattern and another was the cast chocolate block. The samples were coded with three random digits and served randomly on the plate. In this test, the panellist had to choose which chocolate they preferred the most.
The 3D printed constructions and cast chocolate block for Choc-1 (Cadbury dark chocolate) and Choc-2 (Callebaut dark chocolate) are illustrated in Figure 13. As can be seen in the figure, the 3D printed chocolate constructed with various infill percentages (25%, 50% and 100%) were able to support the size and shape of the constructions. Also, the hollow structure was visible in chocolate printed in 25% and 50% infill when the

# 3.10 Ranking for preference evaluation

chocolate was snapped.

Table 4 presents the estimated median based on the Friedman test (nonparametric) and *p*-value for 3D printed dark chocolate samples (at 25%, 50% and 100% infill) in an evaluation of ranking for preferences in terms of appearance and hardness and overall preferences. As can be seen in Table 4, there was a significant difference (p < 0.05) between the preferred appearance of the 3DP samples (Choc-2) as most participants favoured the appearance of sample

Table 4. Recorded median and	p-value of ra	anking of pre	ferences (a	appearance,	hardness a	and overal	l preferences)	based	on
Friedman test for 3DP chocolate	printed in vari	ious infill perc	entages (2	5%, 50% and	d 100%).				

Danking for motoron and	Samples				
Ranking for preferences	3DP25%_IP	3DP50%_IP	3DP100%_IP	p-value	
Appearance	2	2.67	1.33	0.001*	
Hardness	1.66	2	2.33	0.792	
Overall preferences	1.33	2.66	2	0.875	

* $P < 0.05$ . Ranking varied from	1-3 (1 is the most prefer	red sample)
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3DP100%\_IP (1.33) to those of samples 3DP25%\_IP (2.00) and 3DP50%\_IP (2.67). These results indicate that the participants mostly prefer the smooth appearance of the 3D printed chocolate (see Figure 13). As the infill structure is printed at closer to 100% infill, the infill structure provides sufficient support to the top layer and prevents it from any surface deformation (Mantihal *et al.*, 2018). Thus, a smooth and even top layer is produced as the infill percentage increased. The appearance of the 3DP construction was vital as this modality can influence the acceptability of the product.

There were no significant differences (p > 0.05) in the participants' preferred texture (hardness) among the 3DP samples. However, participants indicated their preferences for the hardness of chocolate sample (by bitting the 3D printed chocolate) 3DP25% IP (1.66) as compared to 3DP50% IP (2.00) and 3DP100% IP (2.33). This result corroborates with the finding in Section 7.3.2, indicating that samples printed in 25% infill are less hard than samples printed in 50% and 100% infill. In this case, we found that the participant is likely to choose a modified texture (less hard). The way the texture changes is significant in determining food product acceptance (Jeltema et al., 2016) and 3DP provides freedom to customise a design, modify textures and alter palatibility (Szczesniak, 2002; Devezeaux de Lavergne et al., 2016; Dankar et al., 2018)

In terms of overall preferences, no significance difference (p > 0.05) was found among all 3D printed chocolate (Choc-2) samples with different infill percentages. The decision about overall preferences is based on the participants' satisfaction in the product's appearance (Andersen *et al.*, 2019) and texture (James, 2018). These attributes are essential to determine consumer preferences in chocolate (Sune *et al.*, 2002). Consumers could feel the texture when consuming the 3D printed chocolate. This perception is influenced by varying the infill structure of the construction.

#### 3.11 Paired preference evaluation

Figure 15 represents the results of the paired preference test of the 3D printed Choc-1 in 100% infill and the cast chocolate block, based on textural attribute. No significant difference was identified between the samples as the results indicate that 50% of participants

chose the 3D100%\_IP chocolate and 50% chose the cast samples. This could be because the 3D printed 100% infill chocolate is perceived to be similar to cast samples with no apparent void existing in the printed chocolate (Mantihal *et al.*, 2019). Besides, participants were also asked to specify their reason for choosing the chocolate samples. Participant mainly indicated that the 3D printed sample was less hard than the cast sample.



Figure 15. Distribution of the consumer preferences for texture for 3D printed Choc-1 in 100% infill and cast chocolate block.

In this experiment, the application of 3DFP was successful in fabricating chocolate with different infill percentages, which leads to a textural modification. The 3D printed chocolate attributes (appearance and texture) were appropriate to indicate the participant's perception of the printed product. The outcome from the sensorial experiment was that 3D printed food provided a good impression as participants experienced the real product produced by this new technology. This impression is an indication of a positive perception of a 3D printed food product (Brunner *et al.*, 2018).

#### 4. Conclusion

In this study, several modifications to the 3D printer were necessary. A printer bed (that enabled cold water to flow through the built-in tube inside the printer bed) and water circulation system helped to establish an immediate solidification of chocolate, thus supporting the subsequent layering process while building up the 3D construction. An optimal nozzle height for chocolate printing was found to be the same as the nozzle diameter, 0.78 mm. Cross-support was more effective than parallel -support on creating more stable hexagonal-shaped

constructs. The infill percentage influenced the textural properties of 3D printed chocolate, signified by an increase in force (N) to break the samples as the infill increased. The results showed that 3D printed chocolates (with 100% infill) were less hard than cast chocolates, because of a weak interaction of layers, affected by the consecutive layering during extrusion deposition. The sensorial evaluation revealed that appearance has a significant effect on consumer preferences. However, the consumers also indicated their preference (in terms of hardness) for 3D printed chocolate with 25% infills. A comparison of a cast chocolate sample with a 100% infill printed chocolate sample showed an equal preference for both samples, influences in part by their perceived texture. A further exploratory study regarding consumer acceptance of 3DFP should be pursued in terms of various aspects and types of 3D printed products to enhance consumer acceptance of this novel technology in the domain of the general public.

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