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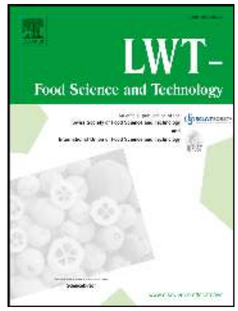

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Investigation on lemon juice gel as food material for 3D printing and optimization of printing parameters

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ABSTRACT: The aim of this paper is to develop a new 3D printing food constructs based on lemon juice gel system. We investigated the effect of potato starch (10, 12.5, 15, 17.5 and 20 g/100g) on the rheological properties and mechanical properties of lemon juice gels. Besides, the influence of printing parameters (nozzle height, nozzle diameter, extrusion rate and nozzle movement speed) on the quality of printed products were also studied. The results show that it is suitable to make the size of the nozzle height the same with that of the nozzle diameter, which could not be regarded as a key factor that affects print quality. An equation is proposed to explain the relationship between extrusion rate, nozzle diameter and nozzle movement speed. In this printing system, the 1 mm nozzle diameter, 24 mm^3/s extrusion rate and 30mm/s nozzle movement speed were found to be the optimal parameters to print 3D constructs matching the target geometry with fine resolution, more smooth surface texture, and fewer point defects with no compressed deformation.

Keywords: 3D food printing; Additive manufacturing; Fruit juice gel; Printing parameters; Rheological properties; NMR; TPA

1. Introduction

3D printing, also known as additive layer manufacturing, is a type of rapid prototyping technology, which involves the integration of computer, direct writ systems, precision transmission, numerical control technologies and material science. Although it was invented in 1980s, only in recent years does it develop rapidly. In the printing process, the material is generally extruded through a nozzle whose position is computer-controlled in accordance with a shape design model. For the production of a product of a particular shape, the traditional process usually requires a model to be produced, while 3D printing eliminates the process. Therefore, compared with the traditional technology, 3D printing has the advantages of time-saving, simple operation and customizable in the whole manufacturing process. In addition, 3D printing provides the possibility to print complex objects with an internal structure, and users have a substantial liberty of design or download their favorite models. In recent years, 3D printing has been widely applied in many fields, such as machinery, biomedicine, polymer, food technology and so on(Chia & Wu, 2015; Lipson & Kurman, 2013). Food 3D printing is expected to be a breakthrough in the popularization of 3D printing industry. Food 3D printing may be an important direction of future food processing. Since the food is closely related to people's lives, consumers will intuitively understand the 3D printing through food(Godoi, Prakash, & Bhandari, 2016; Sun, Zhou, Huang, Fuh, & Hong, 2015).

3D printing provides a new frontier in food processing, helping us to realize and produce new foods with complicated shapes using particular material formulation mixtures and potentially enhancing its nutritional value(Pallottino et al., 2016). Some food materials such as chocolate, dough and meat paste has been utilized to print 3D object(Hao et al., 2010; Wegrzyn, Golding, & Archer, 2012). Sometimes, the printed objects need to be processed or cooked post-printing. Lipton et al. (2015) used transglutaminase and bacon fat as additives to make printable scallop and turkey meat-puree. These final meat products well kept their shape after cooking(Lipton et al., 2010). The researchers also investigated the effect of variations in the amount of butter, yolk and sugar relative to the nominal recipe on the shape stability for sugar cookies after cooking. They reported that yolk concentration contributed to the stability in the X direction(Lipton, Cutler, Nigl, Dan, & Lipson, 2015). Severini et al. (2016) analyzed the first examples of 3D food printing available in literature and reported the production of 3D printed wheat-based snacks enriched with insect powder (Tenebrio molitor) with the aim to improve the quality and the content of proteins(Severini, Carla, Derossi, & Antonio, 2016).

The properties and composition of materials have been considered to be the most important factors in 3D printing process. These materials should be homogenous and have appropriate flow properties for extrusion as well as can support its structure during and after printing process(Godoi et al., 2016; Shao, Chaussy, Grosseau, & Beneventi, 2015). Zhang et al. (2015) used dual-responsive hydrogels to fabricate three-dimensional objects via extrusion from a nozzle in 3D printing. They found gels with a rapid and reversible modulus response to shear stress and to the temperature were suitable for direct-write 3D printing as they were easily extruded out from nozzle tip during printing and could maintain sufficient mechanical integrity to support the next printed layer without deformation(Zhang et al., 2015). Other researchers have come to a similar conclusion(Shao et al., 2015; Wang, Zhang, Bhandari, & Yang, 2017).

Some researchers have also investigated the effects of printing parameters on the geometrical accuracy and dimension of food pattern. Hao et al. (2010) demonstrated a linear relationship between the extrusion rate used in the ChocALM software and the bead diameters obtained. However, these studies do not explicitly account for the relationship between print parameters.

The main aim of this work is exploring the opportunity of 3D printing of a lemon juice gel. Lemon gel can be regarded as a kind of gel-type fudge which is translucent, flexible and chewy. Potato starch has good water retention capacity, transparency and aging resistance properties(Zhang, Zhang, Yang, & Chen, 2001). Thus, in this research starch was chosen as a gelling agent. Printing size parameters such as nozzle diameter size, nozzle height, nozzle movement speed, extrusion rate and material properties (Rheological properties, moisture orientation and texture properties) on the final qualities of the 3D constructs were investigated.

2. Materials and Methods

2.1 Raw Materials

Lemon juice was provided by Jiahao Co. Ltd. Guangdong, China and stored at 4° C. The moisture content of the lemon juice was 59.82 g/100g as determined by the vacuum-drying method. The pH of lemon juice was 2.28. Potato starch were purchased from Shanghai Tianyu Food Co. Ltd. The moisture content was 13.47±0.4 g/100g, 97.5±0.5 g/100g purity with amylose and amylopectin ratios of 25.7±0.2 g/100g and 74.3±0.2 g/100g respectively. Starches were stored at normal atmospheric temperature.

Lemon juice was firstly mixed with different starch content (10, 12.5, 15, 17.5, 20 g/100g). Afterwards, the mixture was completely homogenized by a mixer (ULTRA-TURRAX® IKA® T18 basic, Model: T18BS25, Germany). Then the samples were moved to glass containers and steam cooked for 20 minutes (Center temperature 86±2°C). During the cooking process, the container was wrapped with food grade plastic protective film to prevent the water loss. Finally, the sample was cooled to room temperature to form a weak gel-like structure and stored at 4°C. Then the nuclear magnetic resonance (NMR) analysis, rheological properties, texture profile analysis (TPA), to determine the status of water and printing behavior of stored sample was investigated.

2.2 Testing of material properties

2.2.1 Low-field nuclear magnetic resonance (NMR) analysis

As water distribution and condition have a close relationship with the material structure and rheological properties, thus a low field pulsed NMI 20 analyzer (Shanghai Niumag Corporation, China) at 22.6 MHz was used in this experiment. About 5 g sample was chosen and packed with a thin layer of plastic film. Then they were put into a 10-mm glass tube. and the NMR probe was inserted into the analyzer. Carr–Purcell–Meiboom–Gill (CPMG) sequences were used to measure spin-spin relaxation time T2. Each measurement was performed for three times.

2.2.2 Rheological properties measurements

Rheological measurements of samples were tested by a hybrid rheometer (Discovery HR-3, DHR, TA Instruments, USA) with a parallel plate (diameter=20 mm). The samples were allowed to rest for 2 min after loading and the temperature was maintained at 25℃. Viscosity and shear stress measurements were carried out for all samples in the shear rate ranging from 0.1 to 100 s^{-1}. Shear stress, shear rate, and steady shear (apparent) viscosity (η) were recorded by a RheoWin 4 Data Manager (Rheology Software, Thermo Fisher Scientific, Waltham, MA). The relevant responses of the samples were recorded as functions of shear rate.

Dynamic viscoelastic properties were characterized using small-amplitude oscillatory frequency sweep mode. The frequency was oscillated from 0.1 to 100 rad/s, and all measurements were performed within the identified linear viscoelastic region and made at 0.4% strain. The elastic modulus (G′), loss modulus (G″), and loss tangent (tan δ= G″/G′) were recorded. Experiments were conducted in triplicate for each type of sample.

2.2.3 Texture profile analysis

A texture analyzer (model TA-XT2, Stable Micro System Ltd., Leicestershire, UK) with was used to assess the instrumental texture properties of different samples (2 cm cube printed using 1.0 mm diameter nozzle). The instrument was calibrated with a 1 kg load cell, then fitted with a flat-ended aluminum probe of diameter 25 mm (Code P/25, Stable Micro System Ltd.). The parameters were presented as follow:

pretest speed 5 mm/s, test speed 1 mm/s, post-test speed 5 mm/s, trigger force 5N, at room temperature (25 ± 1°C). All tests were repeated three times.

2.3 Printing process

The 3D printing system composed of the following three major parts: (i) feed hopper with auger mixer and conveyor, (ii) an extrusion system, (iii) and a X-Y-Z positioning system using stepper motors. The nozzle height from the printing bed was achieved by adjusting the whole feeding device. The pressure exerted on the sample was applied via the extruder conveying screw. The samples were extruded onto a polished transparent plastic polymer plate using nozzles of circular shape with diameters of 0.5, 1.0, 1.5 and 2.0 mm. The printing process was conducted at room temperature (25 ± 1°C). The motion and positioning control were provided by a computer with a specifically designed Java program and micro controller.

To assess the effects on the extruded geometry, line tests and cylinder tests were used. Lines of sample were extruded at varying extrusion rates, for same movement rates to determine the appropriate extrusion speed. The cylindrical is a suitable model to evaluate the printing effect, since the printing process has been related to the simultaneous motion of the X axis and the Y axis. Cylinders of sample (Φ20mm×15mm) were extruded at varying extrusion rates, for different movement rates and nozzle diameters, to evaluate print parameters. The test samples were then weighed and calculate the volumetric extrusion rate. The velocity of the nozzle was also measured to calculate the volumetric extrusion rate.

2.4 Statistical Analysis

Analysis of variance was performed and mean comparisons were run by Duncan's multiple-range test using SPSS software (SPSS 19.0; IBM SPSS Statistics, Chicago, IL, USA). Significant differences ($p < 0.05$) between mean values of samples were determined.

3. Results and Discussion

3.1 LF-NMR spin-spin relaxation times (T2) of lemon juice gel

NMR analysis showed the distributions of different states of water in lemon juice gel, which is related to the material structure and rheological properties. A small transverse relaxation time (T_2) indicates a small degree of moisture freedom in the sample and strong binding with solid components. While a large T_2 indicates a large degree of moisture freedom(Schmidt & Lai, 1991). It can be observed from (Fig.1) that there were three peaks in each sample. Three relaxation populations of lemon juice gels were centered at approximately 0.3-20 ms (T_{21}), 20-200 ms (T_{22}), and 200-1000 ms (T_{23}), which were assigned to the bound, partially immobilized, and free water, respectively.

Fig.1 shows that there are quite distinct differences in the moisture distributed in lemon juice gels. The free water relative intensity close to 0, which was not observed to have significant differences in the five treatments. However, the T_{22} began to reduce significantly with the increased potato starch addition. The reason could be higher starch concentration provides more opportunities for water molecules and starch molecules to interact(Jane & Shen, 1993; Tako & Hizukuri, 2002). Ritota et al. (2008) found similar conclusions and suggested that when exact amount of water for gelation process was available in the mixture the maximum strength could be achieved(Ritota, Gianferri, Bucci, & Brosio, 2008). Besides, the water population that was tightly bound (T_{21}) became smaller and changed from two peaks to a single peak when the starch content increased.

Overall from Fig.1 it could be concluded that T_2 decreased with the increase of starch content. This suggest some of the partially immobilized water turned into bound water, indicating that that the interaction between water molecules and starch molecules became more close and a denser network structure was formed as the extra added potato starch increased, which could also be reflected by the increasing of apparent viscosity (Fig.2A), G′ (Fig.2B), hardness and springiness (Fig.3).

3.2 The rheological behavior of the lemon juice gel

The mechanical properties and rheological behaviors of food play an important role during manufacturing, storage, handling, and last but not least, during consumption(Vliet, 2013). During extrusion, gels are subjected to relatively high pressure and mechanical shear forces(Lai & Kokini, 2008). Thus, rheological properties of gels are important indexes to judge the printability(Liu, Zhang, Bhandari, & Yang). A similar conclusion was found that rheological properties significantly affect the printability (Avery et al., 2014; Liu et al.).

As shown in Fig.2A, the apparent viscosity of the lemon juice gel is decreased obviously with the increased shear rate, indicating that the lemon juice gels are pseudoplastic fluids and shear-thinning which is benefit to be extruded through the nozzle. The increase of potato starch content led to a general increase of viscosity, and this will be beneficial for the shape holding of extruded material.

The storage modulus (G') is a measure of the elastic solid -like behavior i.e., samples resistance to deform elastically, while the loss modulus (G'') is the viscous response is the ratio of stress to strain under vibratory conditions. The loss tangent (tanδ= G''/G') is used as a characteristic parameter to illustrate the different viscoelastic behavior(Fischer & Windhab, 2011). A tanδ value smaller than one means predominantly elastic property and greater than one indicates predominantly viscous property(Eidam, Kuhn, & Stute, 1995; Won, Choi, Lim, Cho, & Lim, 2000).

Considering the viscoelastic properties of lemon juice gel, G' was always higher than G'' in the linear viscoelastic region (Fig.2B and C). This indicated that the potent of materials to form elastic gel or gel-like structure and the system of materials is in the state of elastic dominance. In addition, at any oscillatory frequency, G' and G'' significantly increased with increasing potato starch content from 10 g/100g to 20 g/100g. This increase might have been due to the reason that starch granules absorbed water and swell when heated and finally resulted in the formation of a denser gel network structure(Eliasson, 1986). The frequency dependence of G' and G'' gives valuable information about structure. A material that is frequency independent over a large time scale range is solid-like; a true gel system is such material. In contrast, strong frequency dependence suggests a material structure with molecular entanglements that behaves more like a solid at higher frequencies and more like a liquid at lower frequencies(Steffe, 1992). The G' and G'' both gradually increased with the increasing oscillatory frequency, and at the same time the tanδ showed a higher value (Fig.2D). In the printing process, the material is subjected to a very low rotate speed (about 1 rad/s). However, it could be seen that tanδ for all mixtures were smaller than 1; indicating that the material shows more solid-like behavior with poor fluidity. In addition, at the rotate speed of 1 rad/s, the tanδ decreases (0.154 to 0.144). with the increasing of starch concentration (10g/100g to 20g/100g), indicating the formation of stronger network structures and more solid like behavior of its gels.

3.3 Texture profile analysis of the lemon juice gel

It is necessary to study the mastication properties of printed foods which affect people's acceptability. Hardness refers to the force required for a sample to reach a certain degree of deformation. Springiness indicates the ability of a sample to revert to its original shape after deformation. Cohesiveness can be used to indicate the adhesion within the sample; Gumminess can simulate the energy required to break the semi-solid sample into a stable state that can be swallowed(Hurler, Engesland, Kermany, & Škalko-Basnet, 2012; Sandhu, Kaur, & Mukesh, 2010).

The gel strength and apparent viscosity closely related to the starch concentration(Jauregui, Muñoz, & Santamaria, 1995). The textural properties were influenced by starch content, lemon juice gel with different starch content showed considerable variation in textural parameters (Fig.3). With the increase of starch content, the hardness, springiness, cohesiveness and gumminess of lemon juice gel was increased in different extent, resulting in a stronger ability to resist external damage. This is mainly due to the increased concentration of starch led to the increased number of starch molecules per unit volume, and the increased probability of intermolecular hydrogen bonding, resulting in a more compact network structure, so the strength of the gel increased(Nunes, Raymundo, & Sousa, 2006; Zhen-Lei, 2010). Taking into account the taste, the samples with 15 g/100g and 17.5 g/100g potato starch might exert the better mouth feel than 10, 12.5 and 20 g/100g potato starch, considering hardness, springiness, cohesiveness and gumminess values.

3.4 Printing process

3.4.1 Optimization of Potato starch addition

Costakis et al (2016) found that the printed specimen shape retention was closely related to the materials G′. A study done using lead zirconate titanate (PZT) colloidal gels to develop periodic structures through 3D printing found that materials with higher G′ showed better shape retention(Jr, Rueschhoff, Diaz-Cano, Youngblood, & Trice, 2016). An ideal lemon juice gel should have a well-defined network, sufficiently high gel strength and proper viscosity and be able to be printable below the extrusion pressure of the printer and capable of fusing with earlier printed layers, as well as keep the print shape(Godoi et al., 2016).

A high starch content (17.5, 20 g/100g) led to an unsuitable material, which produced a high viscosity and small tanδ. A small tanδ (0.144, 10 g/100g of starch content at 1 rad/s of rotate speed) suggests that the slurry revealed more solid-like behavior and poor fluidity(Tabilo-Munizaga & Barbosa-Cánovas, 2005), resulting in broken deposited lines and difficulty of extrusion (Fig.4D and E). While a low starch content (10, 12.5 g/100g) led to a suboptimal material which had low viscosity and large tanδ. A large tanδ (0.154, 10 g/100g of starch content at 1 rad/s of rotate speed) suggests that the slurry revealed more liquid-like behavior and good fluidity(Tabilo-Munizaga & Barbosa-Cánovas, 2005), resulting in a larger amount of extrusion than the set value and not conducive to maintaining the shape of products (Fig.4A and B). With potato starch addition to 15 g/100g, the printed constructs exhibited the smoothest visual surface texture, better matching with the target geometry, fewer point defects and no compressed deformation (Fig.4C). Based on these observations, the optimal concentration was determined to be 15 g/100g of starch. This corresponded to 8079.3 Pa·s apparent viscosity at 0.1 s^{-1} shear rate, G' of 4924.2 Pa; G" of 760.8 Pa and tanδ of 0.155 at 0.63 rad/s.

3.4.2 Optimization of nozzle height

Nozzle height is the distance between the nozzle tip of the extruder and the deposited top layer. Previous research suggested that the nozzle height greatly influenced the geometry shape of the extrudates(Attalla, Ling, & Selvaganapathy, 2016). Wang and Shaw(Wang & Shaw, 2005) gave an equation to estimate a critical nozzle height (h_c):

$$h_c = \frac{V_d}{v_n D_n} \qquad (1)$$

V_d is the volume of the extruded rate (mm^3/s), v_n is the nozzle movement speed (mm/s), and D_n is the nozzle diameter (mm).

After a lot of experiments in this study, it is considered that the nozzle height is suitable to be same with that of the nozzle diameter, which could not be regarded as a key factor that affects print quality. Under the condition of the same nozzle diameter and nozzle height, the essential reason for the effect on the printing is likely to be the mismatched extrusion rate and printing speed. In an ideal printing process, the extruded material has the same diameter as the nozzle considering there is no shrinking/swelling or expansion, and nozzle height should be as small as possible to ensure that the material can be attached to the previous layer and to avoid the inaccuracy caused by the delayed deposition. Therefore, the nozzle height should be equal to the nozzle diameter as well as the single layer height.

Based on above point of view, the extrusion rate is determined by the nozzle height as well as the nozzle diameter, and it may be more appropriate to change the equation as follows:

$$V_d = \frac{\pi}{4} v_n D_n^2 = \frac{\pi}{4} v_n h_c^2 \quad (2)$$

V_d is the volume of the extruded rate (mm^3/s), v_n is the nozzle movement speed (mm/s), D_n is the nozzle diameter (mm), and h_c is the nozzle height. Khalil et al. reported a similar equation to determine the nozzle movement speed(Khalil & Sun, 2007), however, they did not determine the relationship between nozzle diameter and nozzle height. According to the formula proposed, the print height is selected to be the same size as the nozzle diameter.

3.4.3 Optimization of nozzle diameter

Nozzle diameter directly determines the precision and surface roughness of printing objects. Fig.5 shows the effect of nozzle diameter on printing quality of 3D constructs. Large nozzle diameter resulted in relatively coarse and poor models, while smaller nozzle diameter resulted in relatively delicate but fine models. However, as shown in the Fig.6, to print the same product, the smaller the nozzle diameter, the much longer time it takes. Taking into account the quality of the product and the efficiency of 3D printing, 1.0 mm nozzle diameter was more suitable than others.

3.4.4 Optimization of the extrusion rate and the nozzle movement speed

Extrusion rate and the nozzle movement speed affect the 3D printing simultaneously, as they change the amount of extrusion per unit length per unit time. The effect of extrusion rate on the 3D printing was investigated as shown in Fig.7. A high extrusion rate (28 mm^3/s) led to wavy lines which had larger diameter (Fig.7A), resulting an overlap and large deviation when printing a larger height product. While a low extrusion rate (20 mm^3/s) led to discontinuous lines (Fig.7C), resulting collapse and considerable difference between the set target and actual product. A suitable extrusion rate can achieve a smooth line with uniform diameter (Fig.7B). In 3.4.2 an equation is proposed:

$$V_d = \frac{\pi}{4} v_n D_n^2 = \frac{\pi}{4} v_n h_c^2 \qquad (2)$$

V_d is the volume of the extruded rate (mm^3/s), v_n is the nozzle moving speed (mm/s), D_n is the nozzle diameter (mm), and h_c is the nozzle height, equal to the diameter of nozzle. In equation, V_d is related to v_n. According to this equation, we also investigated and confirmed the relationship between the appropriate extrusion rate and the nozzle movement speed at different nozzle diameters (Fig.8). Obviously, there is a positive correlation between the extrusion rate and the nozzle moving speed, and the data obtained from the experiment are fitted well with the equation, suggesting this equation can be used to estimate the optimal extrusion speed on the basis of known nozzle movement speed and nozzle diameter. When changing the nozzle movement speed, it is expected to make the printing as fast as possible to improve the printing efficiency. However, when the nozzle movement at a high speed (＞30 mm/s), the extrusion rate is less than the predicted value. As shown in Fig.9, the quality of the product did not change significantly until the nozzle moving speed increased to 35mm/s. Too high speed (35 mm/s) can cause dragging of the extruded filaments of products causing breaking of the extruded slurry filaments (Fig.9E).

In this work, the extruded rate (24 mm^3/s) and the nozzle moving speed (30 mm/s) was found to be suitable for 1.0 mm diameter as they produced precise pattern. Some 3D constructs were printed under these conditions as shown in Fig.10.

4. Conclusions

It was found that the rheological behavior and mechanical property of lemon juice gel with 15 g/100g potato starch was suitable for 3D printing of designed objects in this study. Besides material properties, the result of process optimization for 3D printing confirmed that the nozzle diameter, the nozzle movement speed and the extrusion rate affect the product quality of the 3D printing. The nozzle height is not considered to be a factor affecting print quality. A new equation is proposed to explain the relationship between the nozzle diameter, the nozzle movement speed and the extrusion rate. The nozzle diameter (1 mm), the extruded rate (24 mm^3/s) and the nozzle movement speed (30 mm/s) were the optimal parameters to provide well printed lines and to obtain exquisite products. What's more, as a gel product, the success of lemon gel in 3D printing provides some guidance for other gel and starch products in 3D printing.

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Figure Captions

Fig.1 NMR signal (T_2) for 3D printed lemon juice gels at different potato starch concentration (□ in Black: 10 g/100g; ○ in Red: 12.5 g/100g; △ in Blue: 15 g/100g; ▽ in Pink: 17.5 g/100g; ◇ in Green: 20 g/100g)

Fig.2 Rheological behavior (A. Apparent viscosity, B. G', C. G" and D. tanδ of the lemon juice gel at different potato starch concentration (□ in Black: 10 g/100g; ○ in Red: 12.5 g/100g; △ in Blue: 15 g/100g; ▽ in Pink: 17.5 g/100g; ◇ in Green: 20 g/100g)

Fig.3 Texture characteristics (A. Hardness, B. Springiness, C. Cohesiveness and D. Gumminess) of the lemon juice gel at different potato starch concentration (10, 12.5, 15, 17.5 and 20 g/100g).

Fig.4 Different geometrical shapes of 3D printed lemon juice gel samples at different potato starch concentration (A=10 g/100g, B=12.5 g/100g, C=15 g/100g, D=17.5 g/100g, E=20 g/100g)

Fig.5 Geometrical shape of printed lemon juice gel samples with different nozzle diameter (A=0.5 mm, B=1.0 mm, C=1.5 mm, D=2.0 mm)

Fig.6 The time spent in printing the same cylinder (Φ20mm×15mm) with different nozzle diameters (A=0.5 mm, B=1.0 mm, C=1.5 mm, D=2.0 mm)

Fig.7 Line test and cylinder test of extruded lemon juice gel samples at varying extrusion rates (A and a=20mm^3/s, B and b=24mm^3/s, C and c=28mm^3/s)

Fig.8 Relationship between the optimal extrusion speed and the nozzle movement speed of different nozzle diameters (□ in Black: Experimental values of 0.5 mm nozzle diameter; ○ in Red: Experimental values of 1.0 mm nozzle diameter; △ in Blue: Experimental values of 1.5 mm nozzle diameter; Line in Black: Predicted values of 0.5 mm nozzle diameter; Line in Red: 1.0 mm nozzle diameter; Line in Blue: 1.5 mm nozzle diameter)

Fig.9 Geometrical shape of printed lemon juice gel samples with different nozzle moving speed (A=15mm/s, B=20mm/s, C=25mm/s, D=30mm/s, E=35mm/s)

Fig.10 Pictures of some products printed at 24 mm^3/s extruded rate, 30 mm/s nozzle moving speed and 1.0 mm nozzle diameter (A. Anchor, B. Gecko, C. Snowflake, D. Ring, E. Tetrahedron)

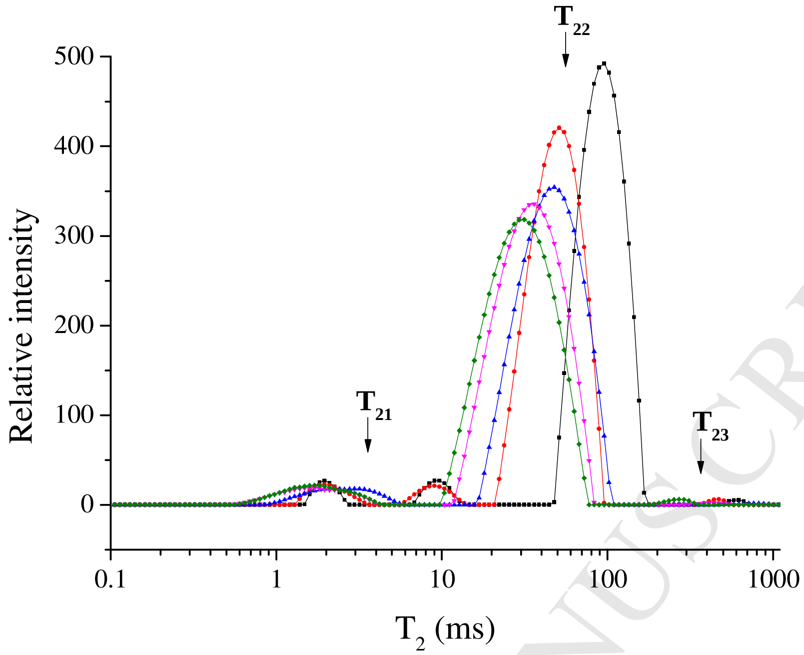
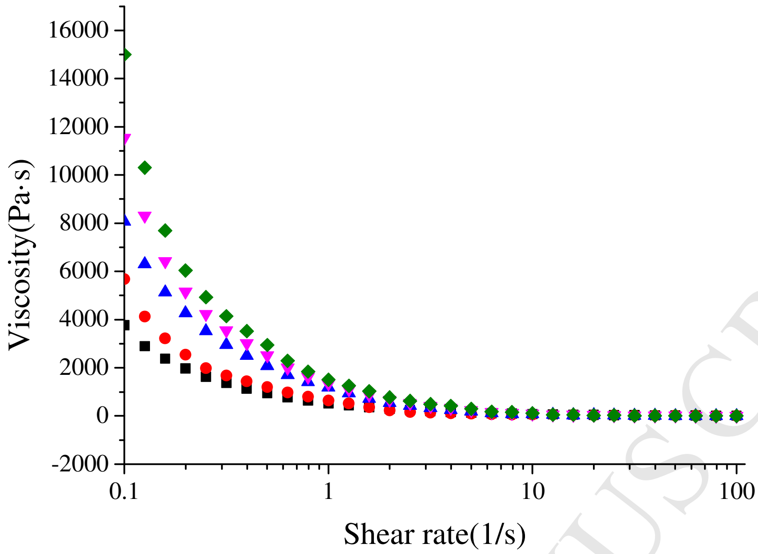
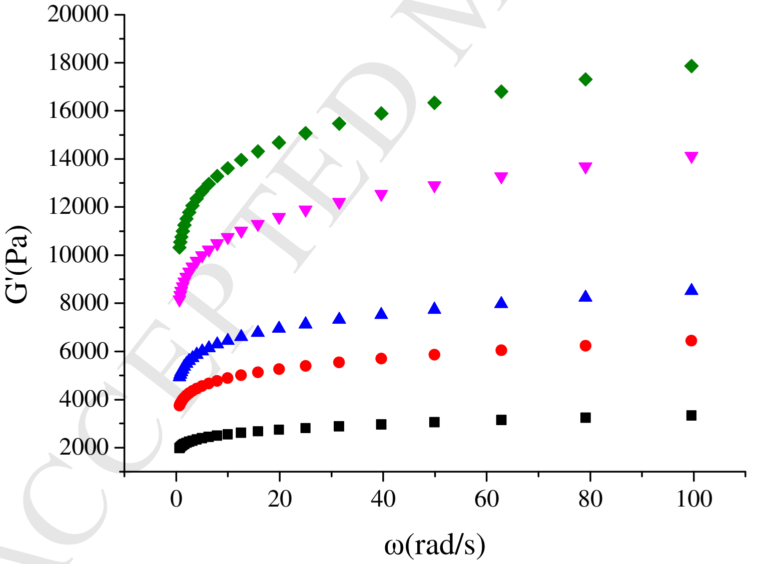


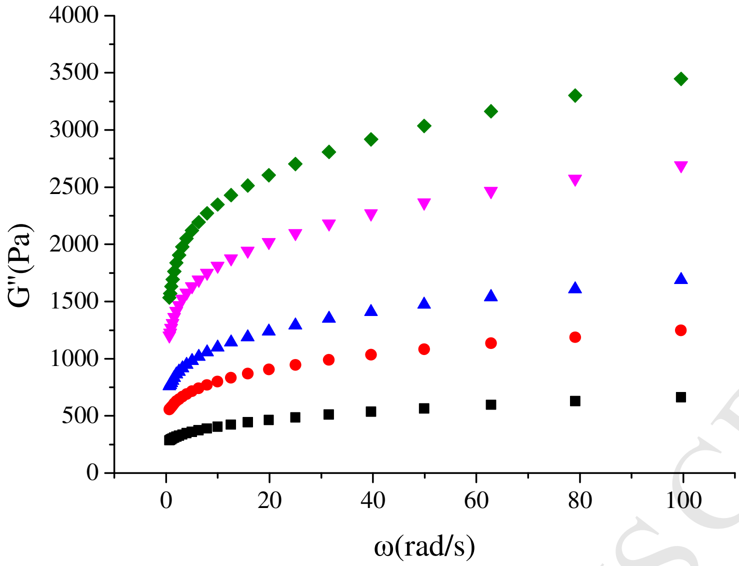
Fig.1 NMR signal (T_2) for 3D printed lemon juice gels at different potato starch concentration (□ in Black: 10 g/100g; ○ in Red: 12.5 g/100g; △ in Blue: 15 g/100g; ▽ in Pink: 17.5 g/100g; ◇ in Green: 20 g/100g)


Viscosity(Pa·s)
16000
14000
12000
10000
8000
6000
4000
2000
0
-2000
0.1
1
10
100
Shear rate(1/s)

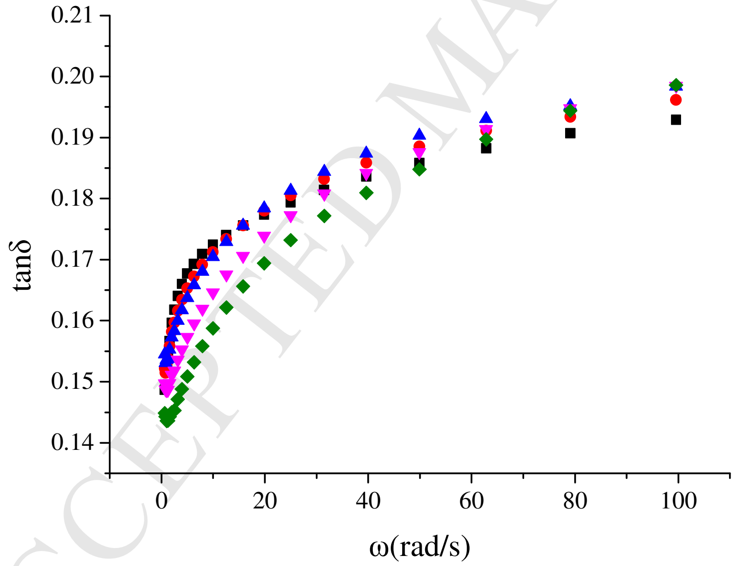
A


G'(Pa)
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
20
40
60
80
100
ω(rad/s)

B



C



D

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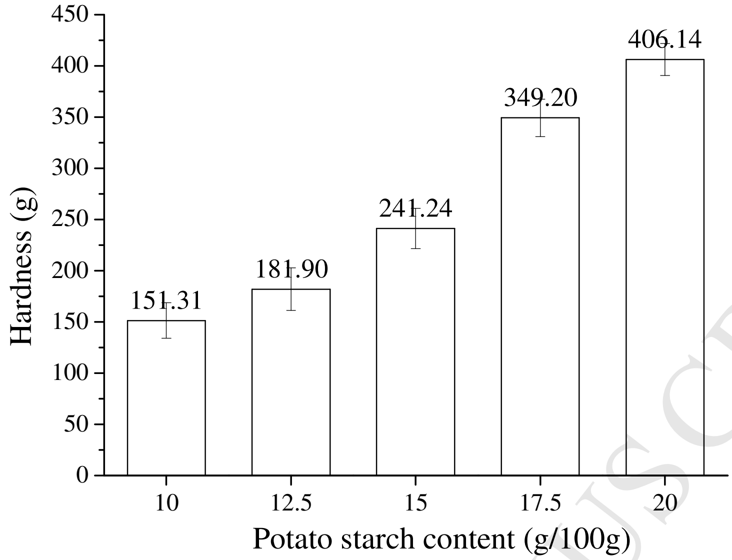
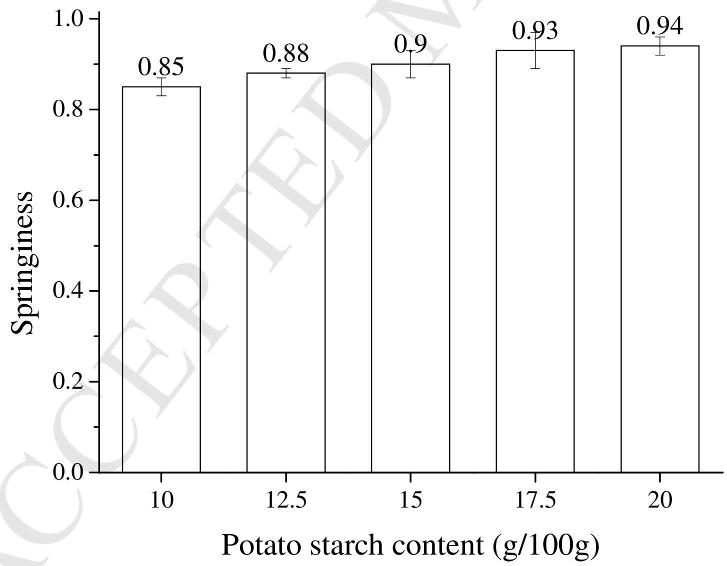
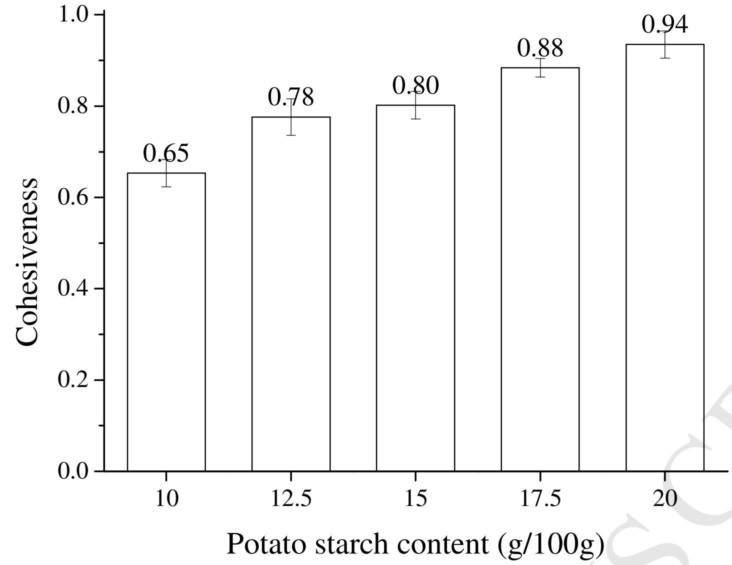

450
400
350
300
250
200
150
100
50
0
Hardness (g)
151.31
181.90
241.24
349.20
406.14
10
12.5
15
17.5
20
Potato starch content (g/100g)

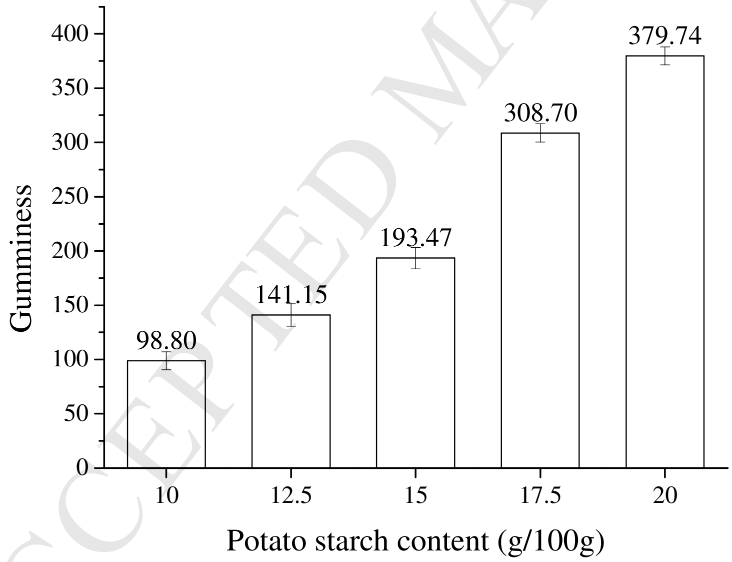
A


1.0
0.8
0.6
0.4
0.2
0.0
Springiness
0.85
0.88
0.9
0.93
0.94
10
12.5
15
17.5
20
Potato starch content (g/100g)

B



C



D

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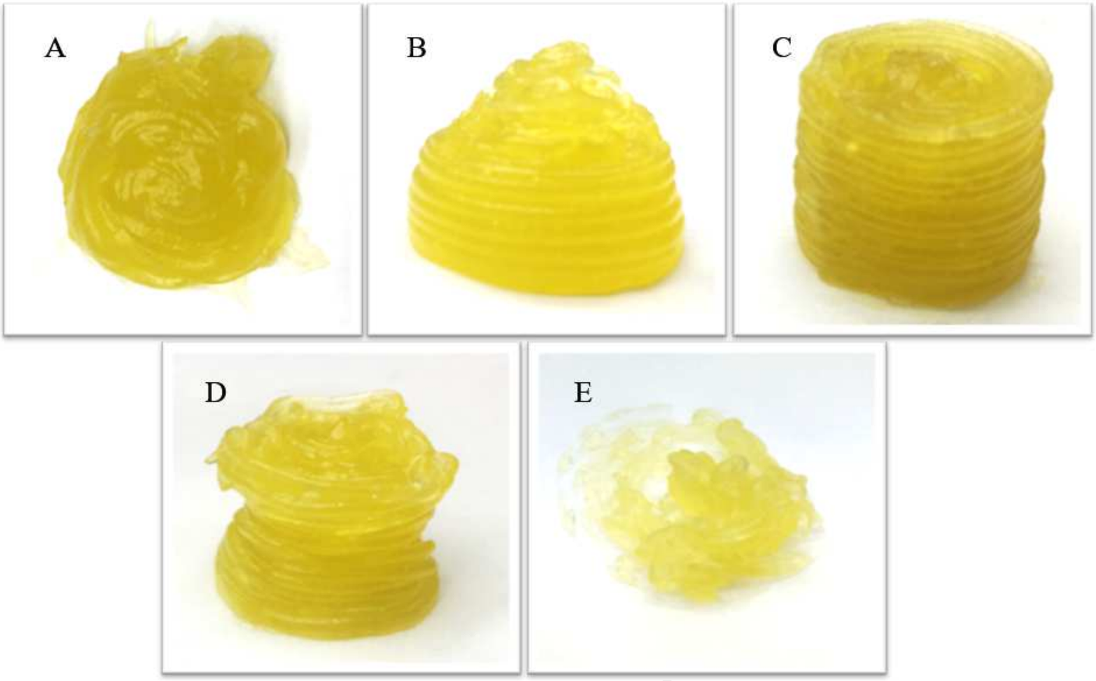


Fig.4 Different geometrical shapes of 3D printed lemon juice gel samples at different potato starch concentration (A=10 g/100g, B=12.5 g/100g, C=15 g/100g, D=17.5 g/100g, E=20 g/100g)

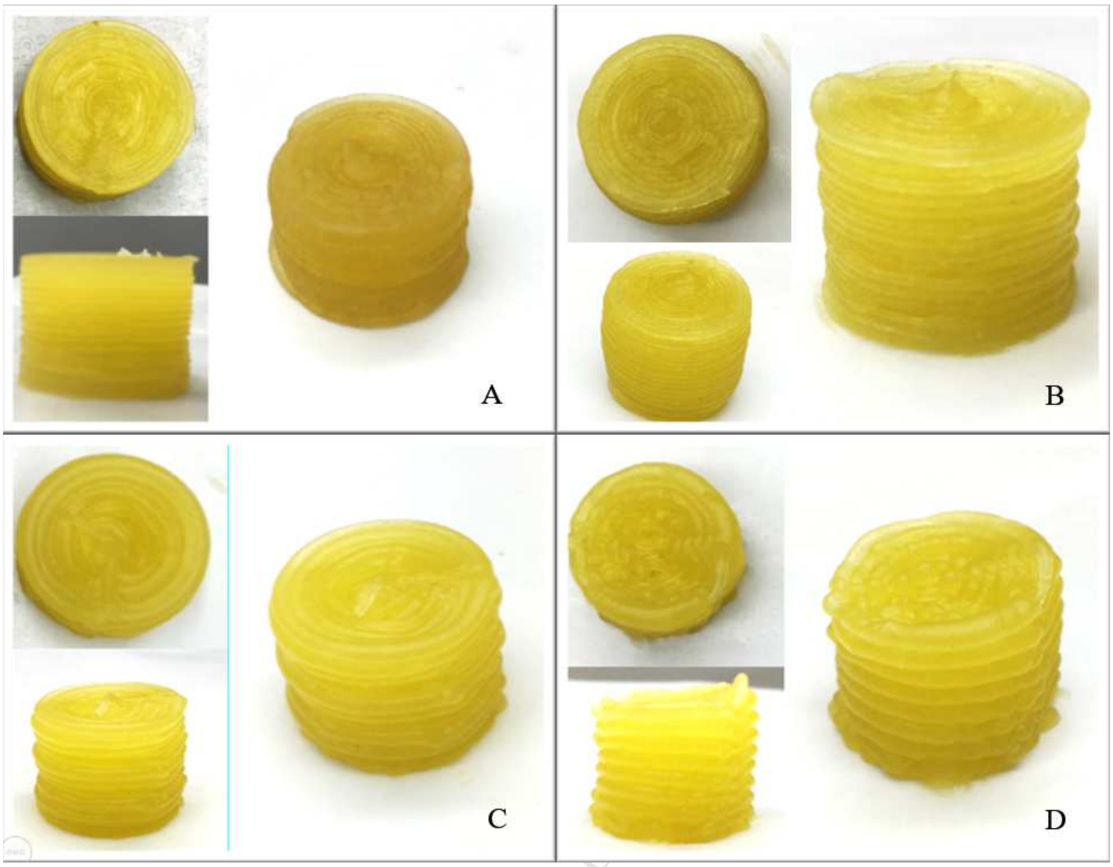


Fig.5 Geometrcal shape of printed lemon juice gel samples with different nozzle diameter (A=0.5 mm, B=1.0 mm, C=1.5 mm, D=2.0 mm)

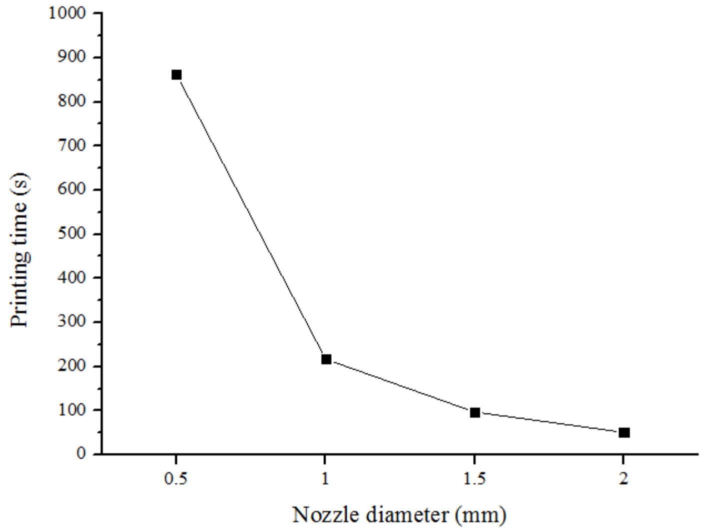
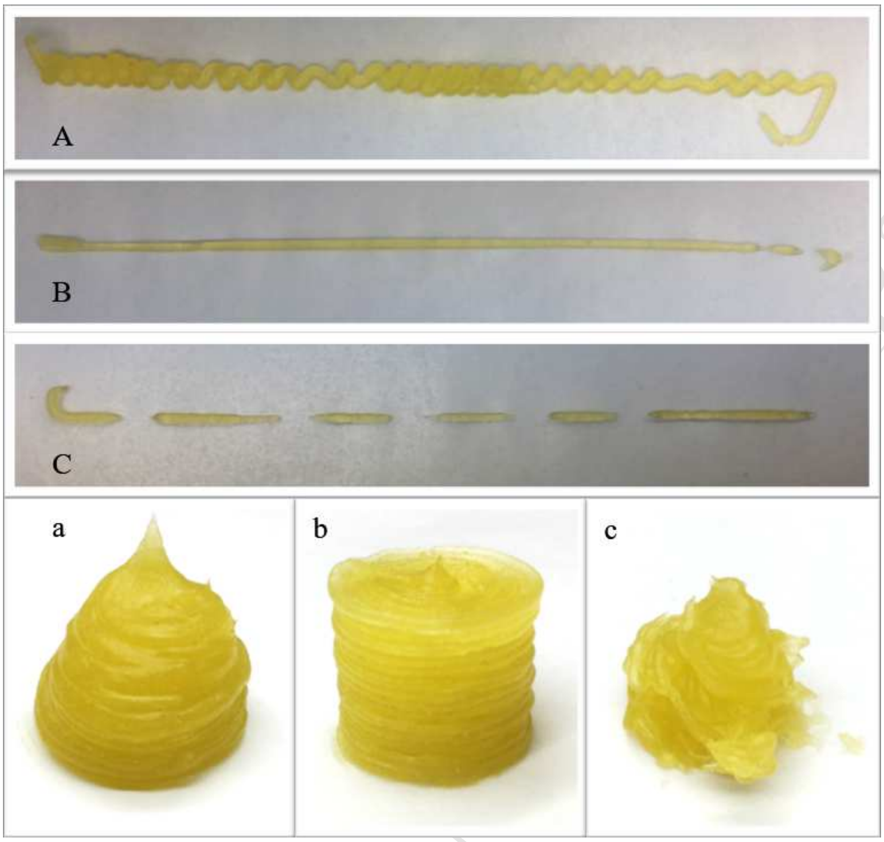


Fig.6 The time spent in printing the same cylinder (Φ20mm×15mm) with different nozzle diameters (A=0.5 mm, B=1.0 mm, C=1.5 mm, D=2.0 mm)

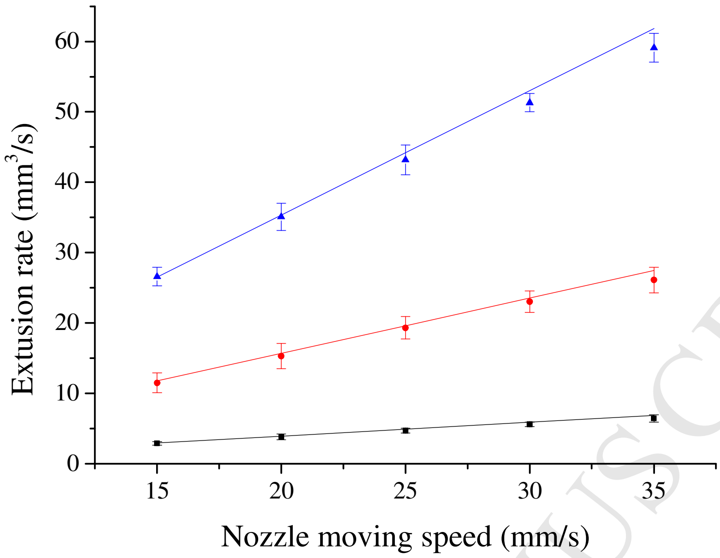
558

559 

560 Fig.7 Line test and cylinder test of extruded lemon juice gel samples at varying

561 extrusion rates (A and a=20mm^3/s, B and b=24mm^3/s, C and c=28mm^3/s)

562



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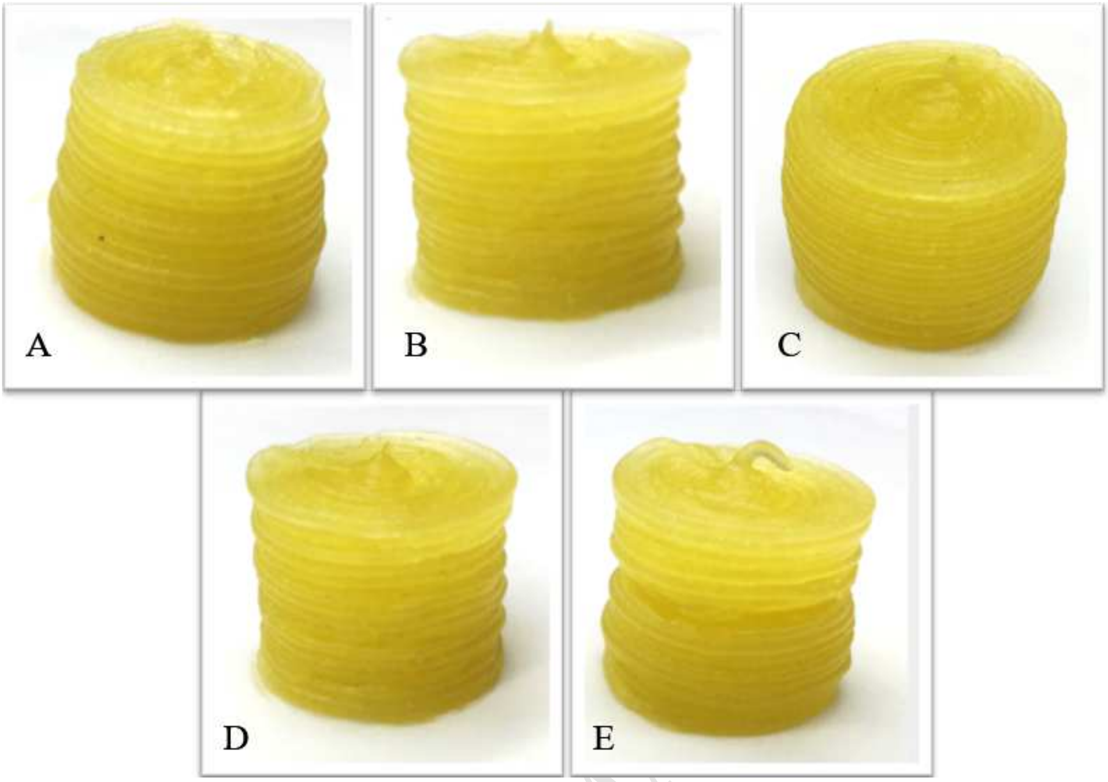

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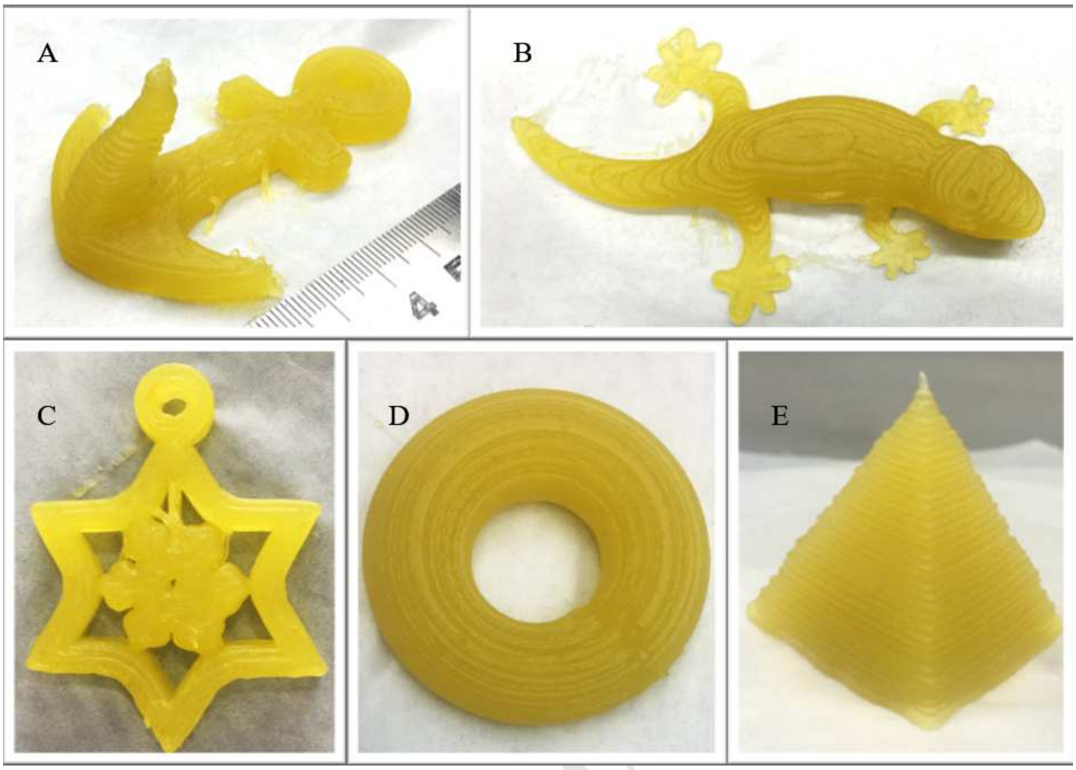

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Highlights:

- A lemon juice gel was investigated as food material for 3D printing.
- Rheological properties were used as indicators to determine printability.
- 3D Printing parameters were optimized.
- An equation was proposed to explain the relationship of printing parameters.
- Providing a basic research on 3D printing for other gel and starch products.