

Potential of 3D printing for food design and manufacture



Korea University
Hyun-Jin, Park



CONTENTS

- 1 Overview of 3D Food Printing
- 2 Research Areas in 3D Food Printing
- 3 Future Direction



01

CHAPTER

Overview of 3D Food Printing

Major research institutes



Australia	Italy	
▪ Queensland University	▪ Deakin University	▪ Foggia University
Israel	China	
▪ Hebrew University	▪ Jiangnan University	▪ Wuhan University
		USA
		▪ Columbia university
		▪ US Army Natick Soldier Research
		Korea
		▪ Korea university
		▪ Ewha Womens University
		Japan
		▪ Yamagata University
		▪ Chungbuk National University

Key researchers

 Australia



Dr. Bhesh Bhandari

Professor, University of Queensland
Editor, Journal Food Engineering

Major Activities

- Collaborating in USA, Ireland, Malaysia, India, France, Vietnam and China.
- Highly cited researcher in his field by Thomson Reuter in 2015.
- 17,000 times citation with an h-index of 63.
- Authored more than 400 papers including 40 book chapters.

Research Field

- Sensory evaluation, Texture Properties, rheological and tribological properties, 3D printing of meat

 Italy



Dr. Antonio Derossi

Professor, Foggia University


Major Activities

- 73 International peer-review publications.
- Collaboration with Schmidt Institute of Physics of the Earth of Russian Academy of Sciences
- Professional experiences based on research activity in food science and technology

Research Field

- Plant Tissue, Personalized food, Edible insect, Variables in 3D food printing, statistical description of food structure

Key researchers

 Israel



Dr. Ido Braslavsky

Professor, The Hebrew University

Major Activities

- Co-founder of the SavorEat (3D food printing company).
- Developed the first single-molecule DNA sequencer.
- He is currently on the governor's board of the international cryobiology society

Research Field

- Ice-binding proteins, Cryobiology, Food biophysics, Frozen systems, 3D Food printing

 Korea



Dr. Hyun Jin Park

Professor, Korea University

Editor, Journal of Food Bioscience

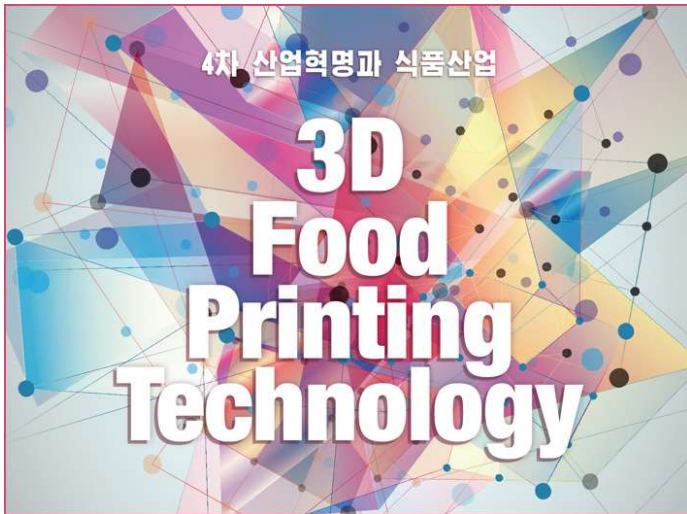
Major Activities

- IFT and IUFOST Fellow
- 15,500 times citation with an h-index of 65.
- 226 International peer-review publications.
- Collaborating in India, Cuba, China, Japan, Thailand, Vietnam and USA.

Research Field

- Classification of the printability, Material Texturization, Post-processing, Nanotechnology, Plant cell, Meat substitute

[2017] 3D Food Printing Symposium in Korea



Laboratory startup

YOLILO minimizes all resources put into the kitchen

YOLILO is a food tech startup that designs time, effort and space for cooking.



Company name	YOLILO Co., Ltd.
CEO	Hyun Woo Kim
Established date	2018.11. 30.

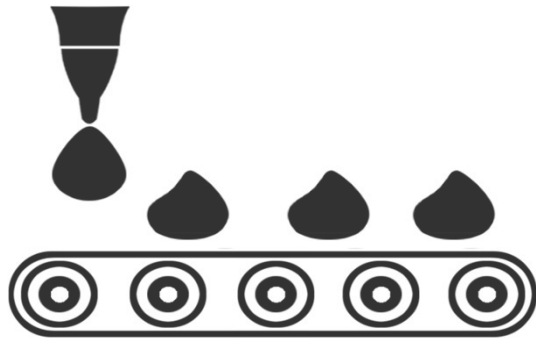
Our Partner



Products



The Fourth Industrial Revolution



3rd industrial revolution

- Mass production
- Technical advance in FT



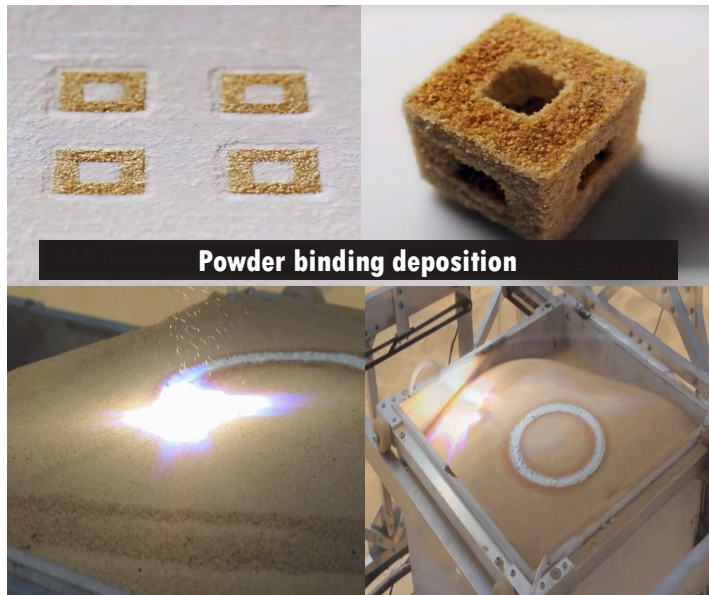
4th industrial revolution

- Small quantity batch production
- Individual customized service
- Advanced food science technology
- Technology integration

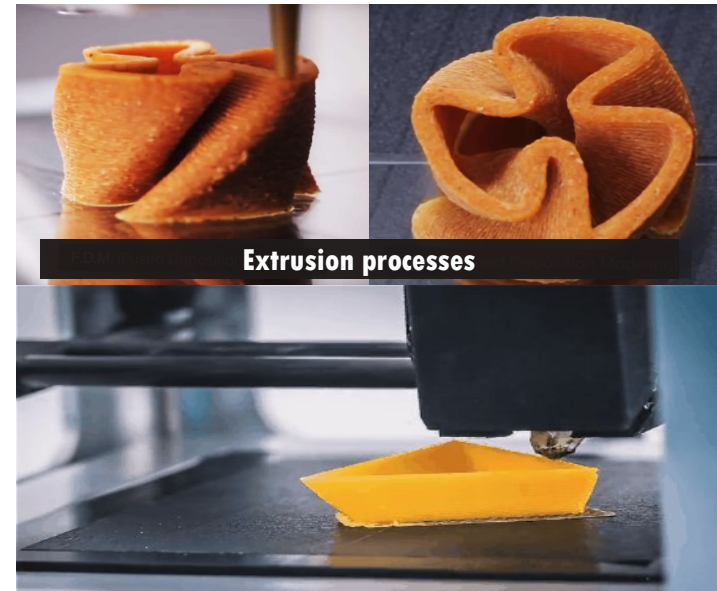
What is 3D Food Printing?

- Technology to fabricate custom-designed food products from 3D digital design and nutritional data in a layer-by-layer manner.

3D Food Printing Technologies

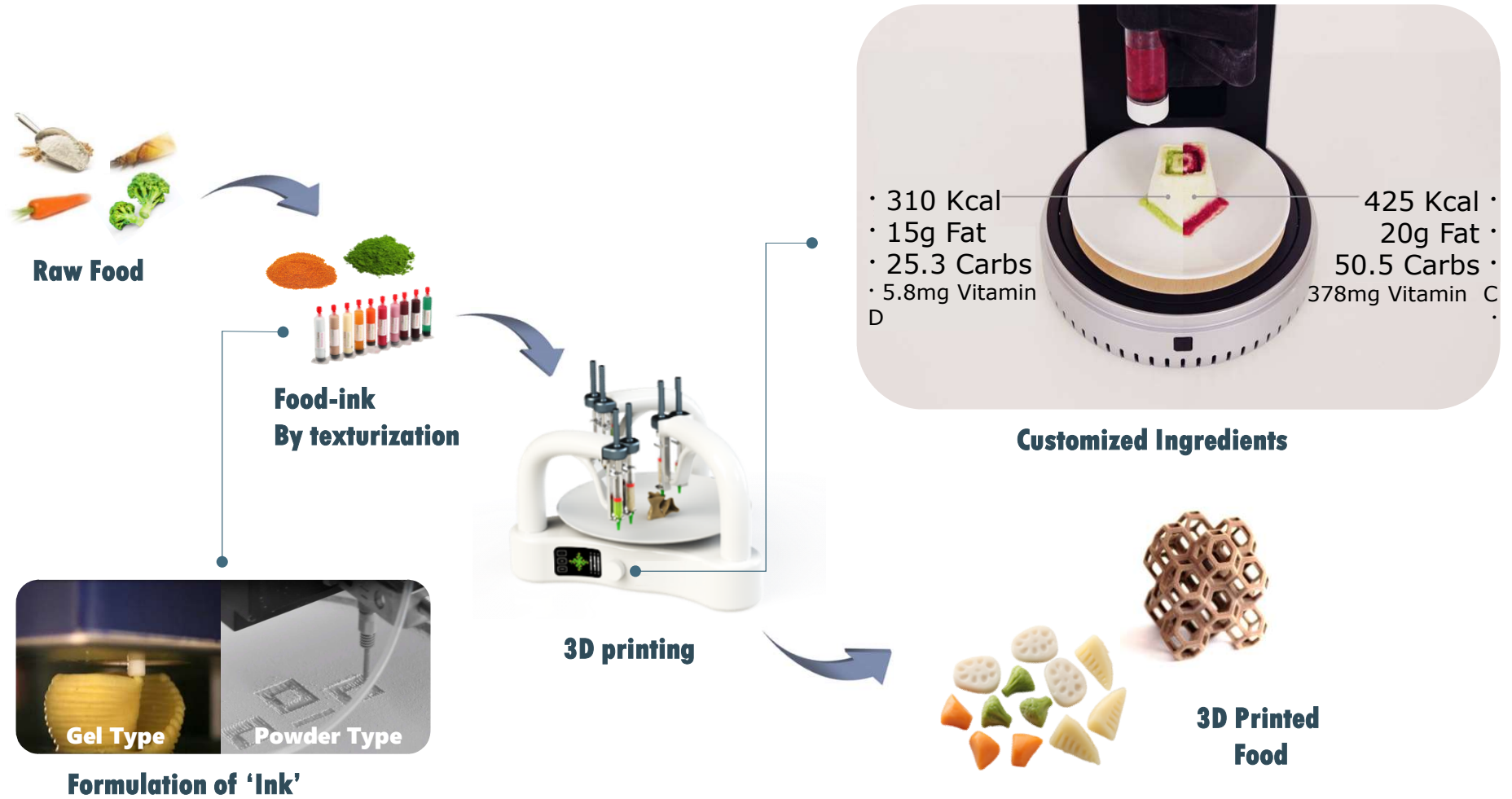


- Selective Laser Sintering (SLS)
- Liquid Binding (LB)

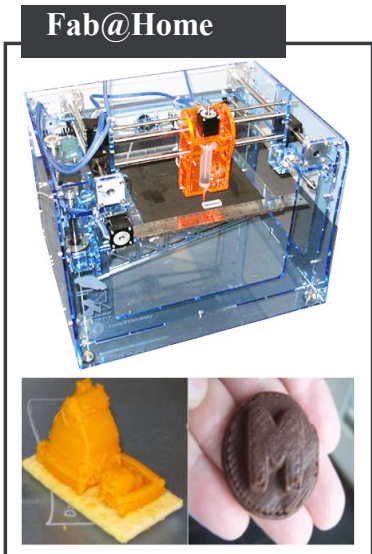
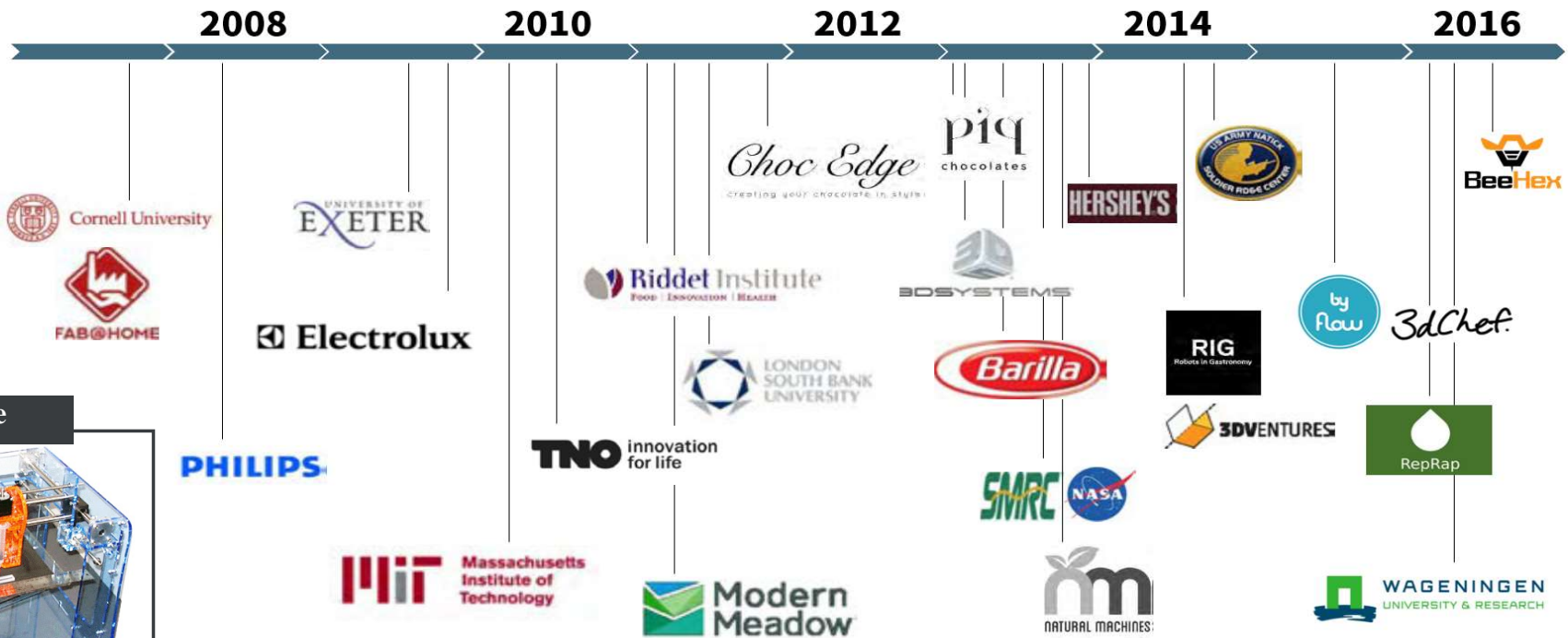


- Fused Deposition Modelling (FDM)
- Soft-Materials Extrusion

Overview of 3D Food Printing



History of 3D Food Printing Technologies



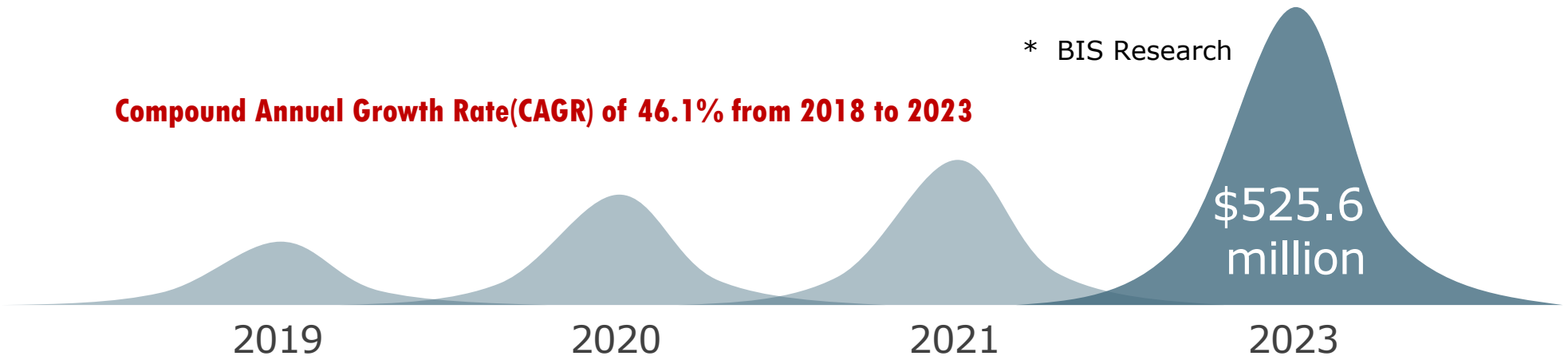
Why 3D printing?

Why 3D printing?



- Less labor
- Less cost
- Time-saving

Market size



- The global 3D food printing market is expected to reach US\$+526.6 million by 2025, rising at a compound annual growth rate (CAGR) of +46.1% from 2018 to 2025
- Currently, the 3D food printers are mostly used to print chocolates, candies, and bread products due to the rise in demand of customized chocolates and cakes from the consumers.

3D Food Printing Market Key Developments

- In terms of geography, Europe is dominating the market due to the rapid adoption of the technology by the consumers.
- Barilla, the leading Italian pasta manufacturer developed a 3D printer capable of printing a variety of differently shaped pasta.



KALPIS 22 PIECES
€ 55.67



OVO 18 PIECES
€ 45.10



Pasta

SALIX 12 PIECES
€ 30.67

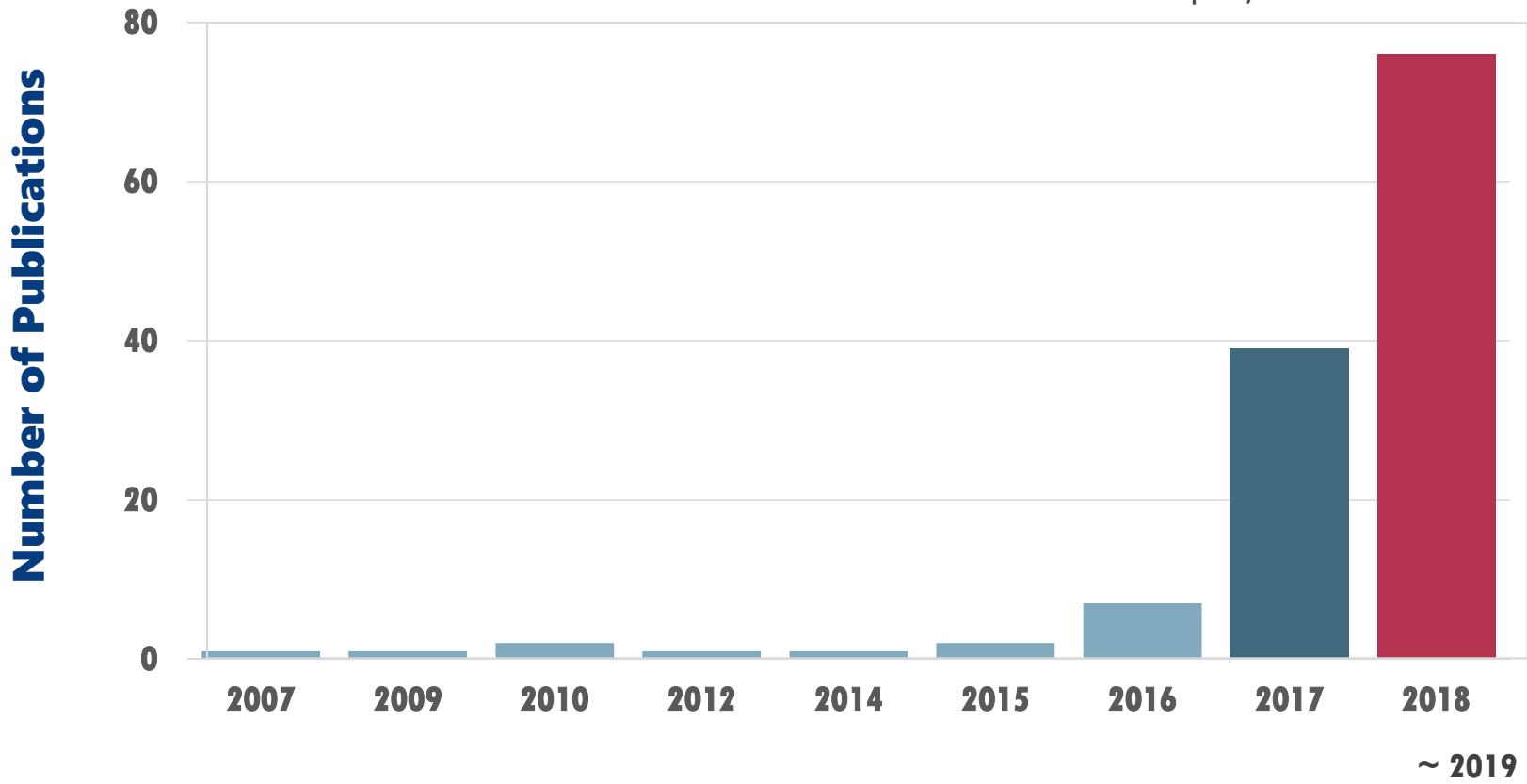


SEA URCHIN 16 PIECES
€ 36.44



Research on 3D Food Printing

Source: Scopus, ScienceDirect



02

CHAPTER

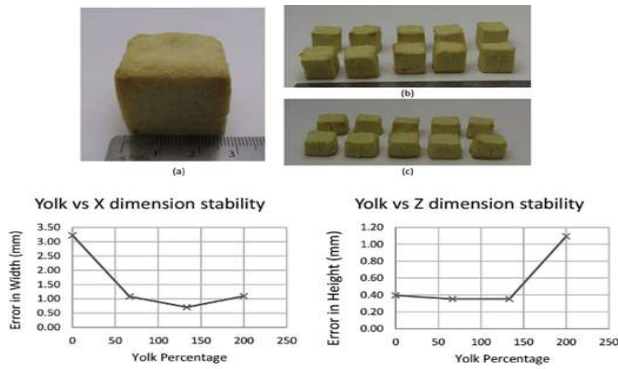
Research Areas in 3D Food Printing In Korea university since 2013

「 **Finding 1** 」

Classification of the printability

Assessment of the printability

➤ There is no technology to demonstrate the printability of the materials for 3D printing.

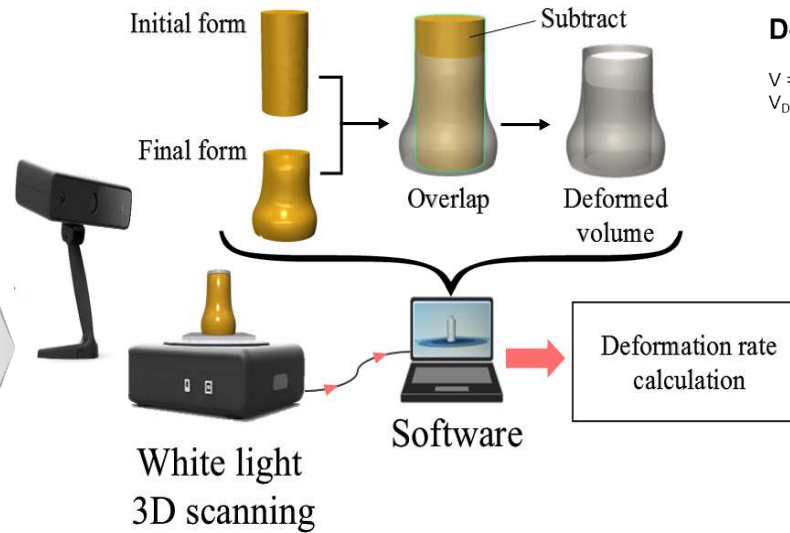


* Trends in Food Science & Technology 43 (2015) 114-123



Figure 4. The chocolate square with good layer-by-layer bond and geometry accuracy. Figure 5. The chocolate square with poor geometrical accuracy.

* Virtual and Physical Prototyping, Vol. 5, No. 2, June 2010, 5764



$$\text{Deformation rate (\%)} = (V_D/V) \times 100 (\%)$$

V = The volume of 3D fabricated objects

V_D = The volume of deformed shape by comparison with the initial form

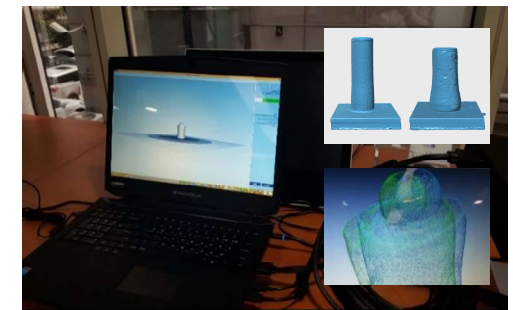


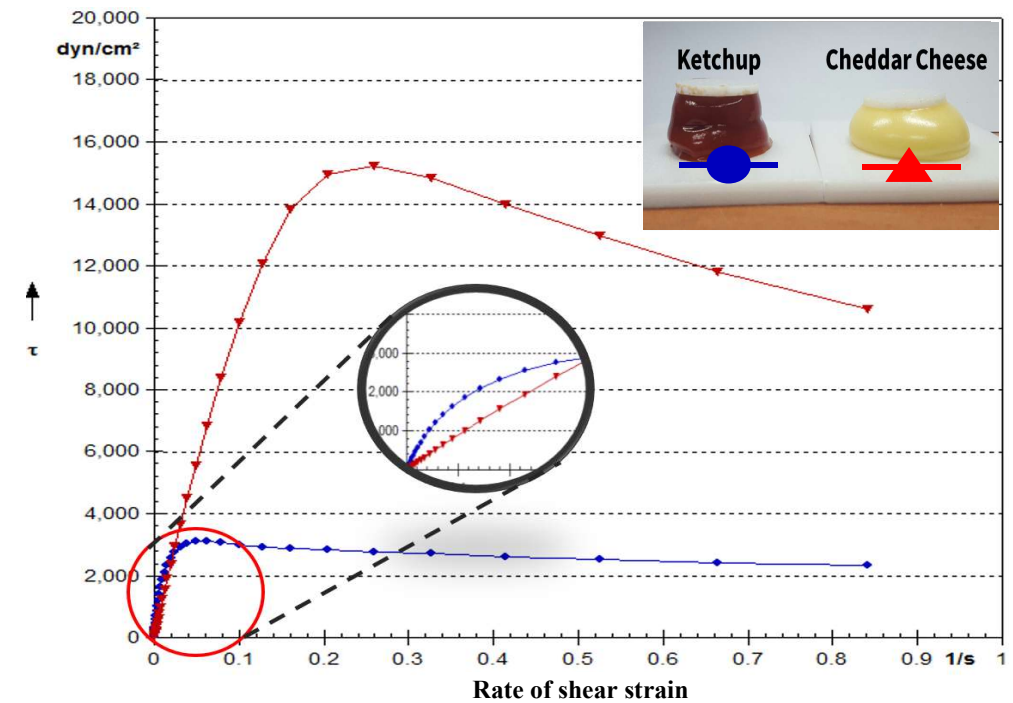
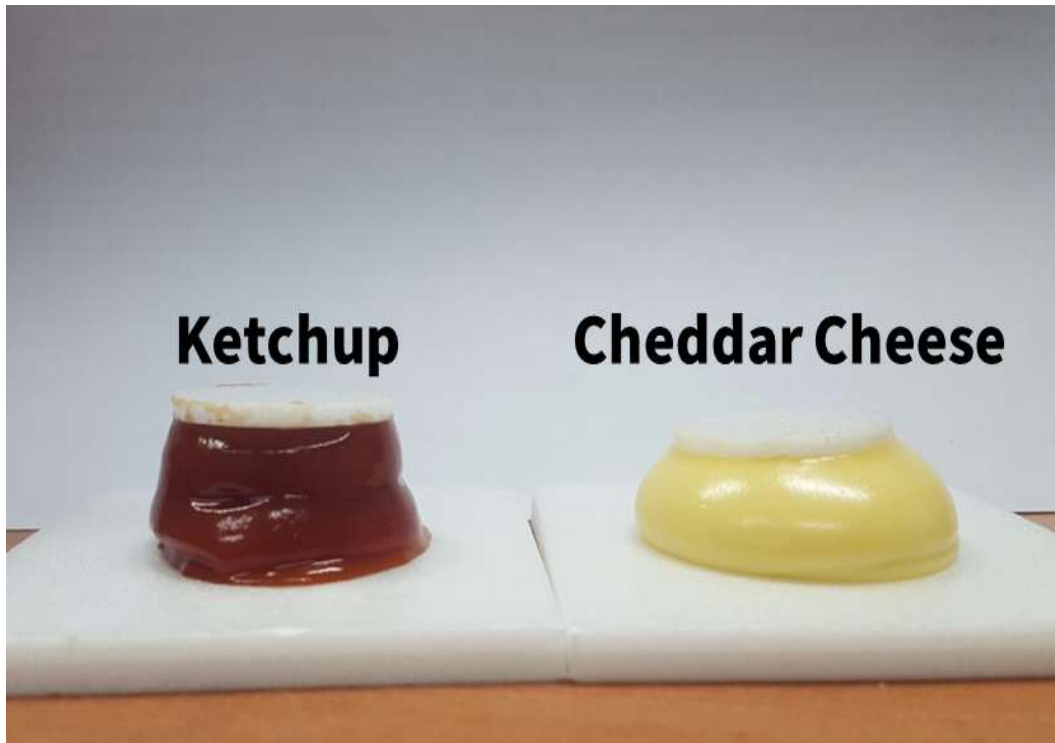
Fig. Schematic diagram of white light 3D scanning and the software for dimensional stability assessment.

* Kim, H. W., Bae, H. J., & Park, H. J. (2017). Journal of Food Engineering, 215, 23-32.

➡ But still complicated and takes a long time

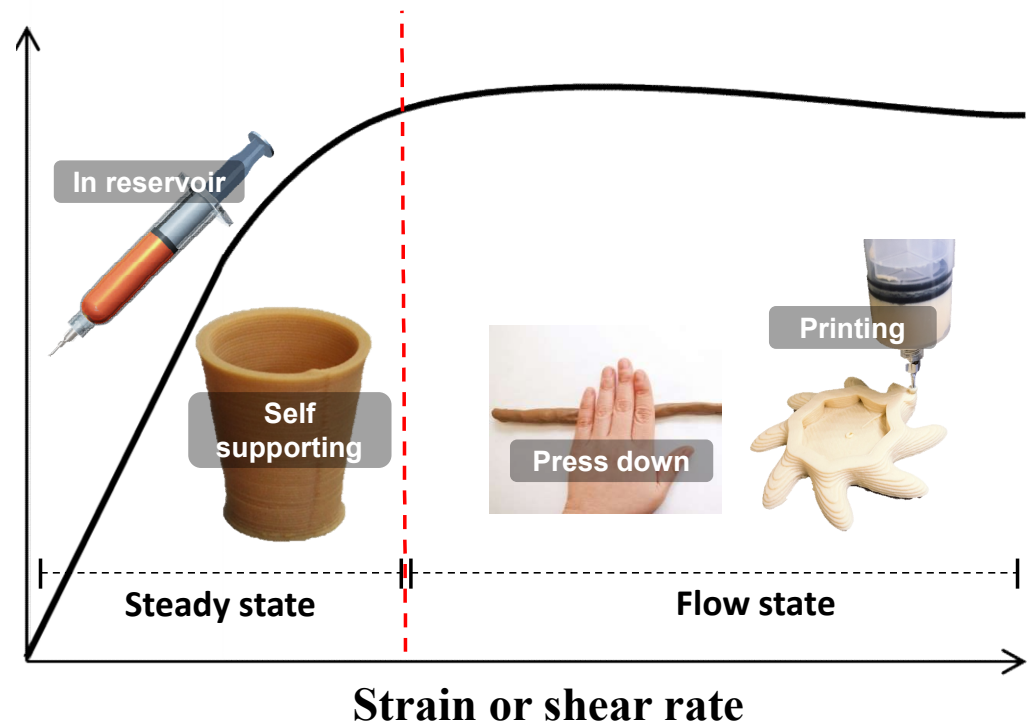
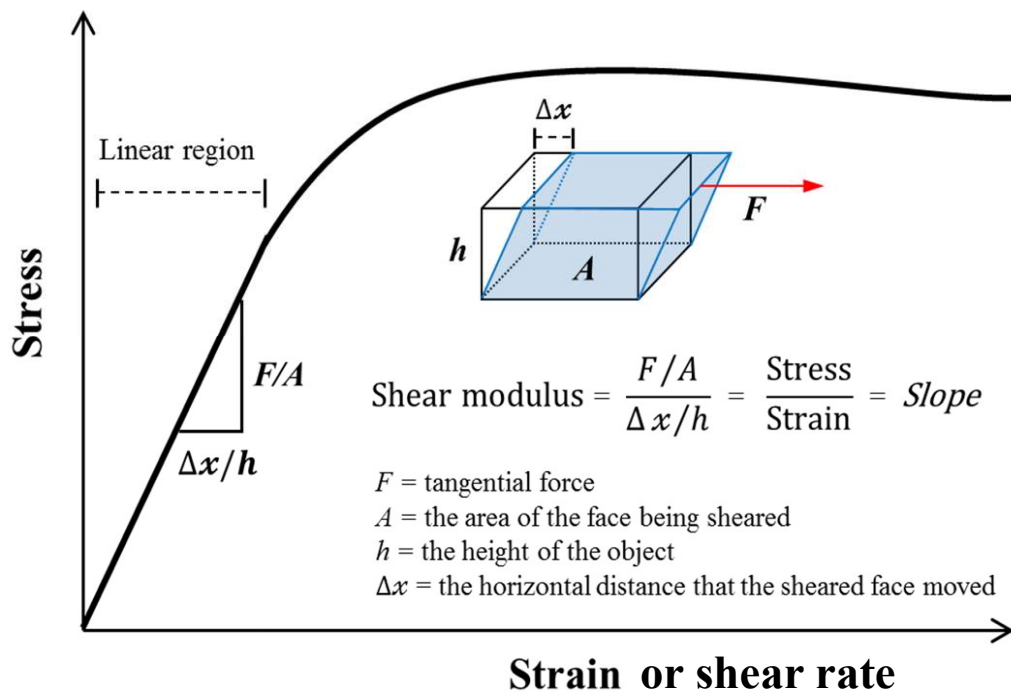
dimensional stability

- Key findings about dimensional changes during the printing process.
- In general, ketchup has a lower viscosity than cheddar cheese.
- However, at very low rate of shear strain, ketchup has a higher viscosity than cheddar cheese.



Shear modulus

- Shear modulus could reflect deformation behavior of 3D fabricated objects which slowly collapse (low shear rate) by its own weight without external force.



Dimensional Stability by Deformation Range

* In our previous study, methylcellulose was selected as the standard for measuring printerability among 8 hydrocolloids.

- **Methylcellulose(MC)** mixtures completely simulated deformation ranges of all food samples as they showed similar features of deformation to various structures of samples.

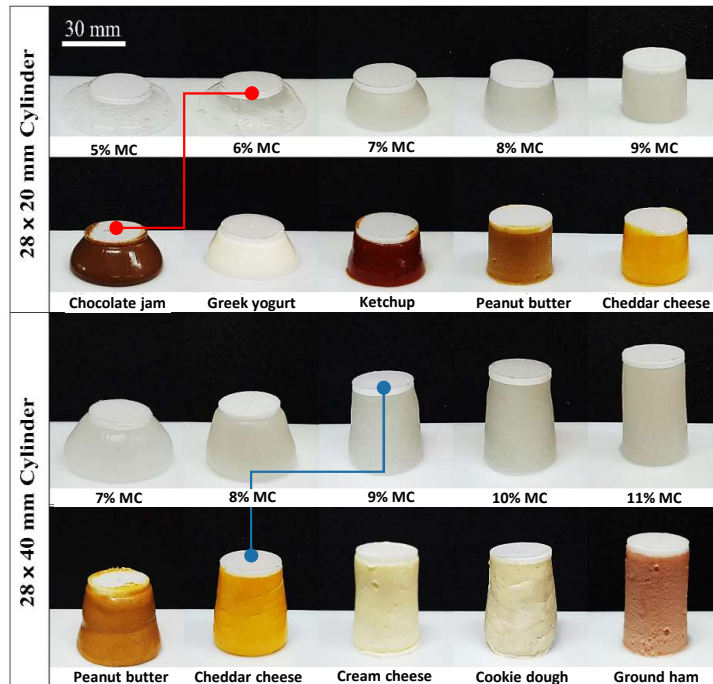


Fig. Deformation behavior of the reference material and experimental foods.

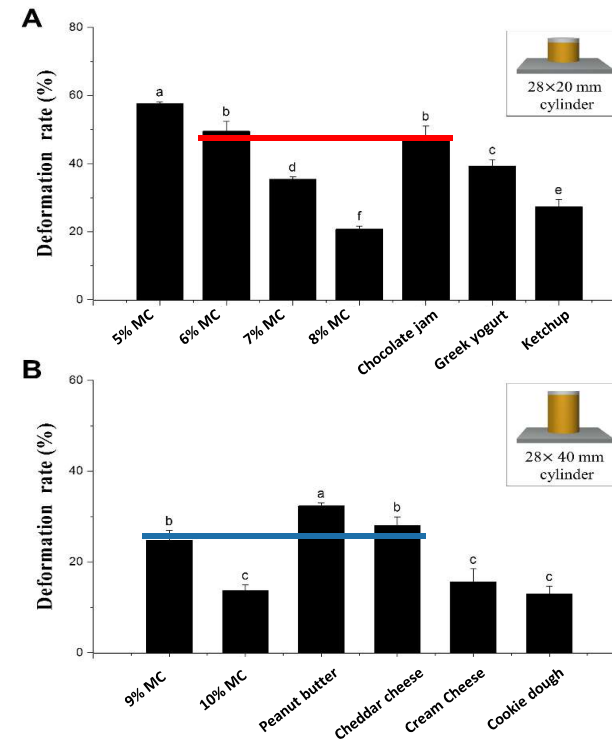
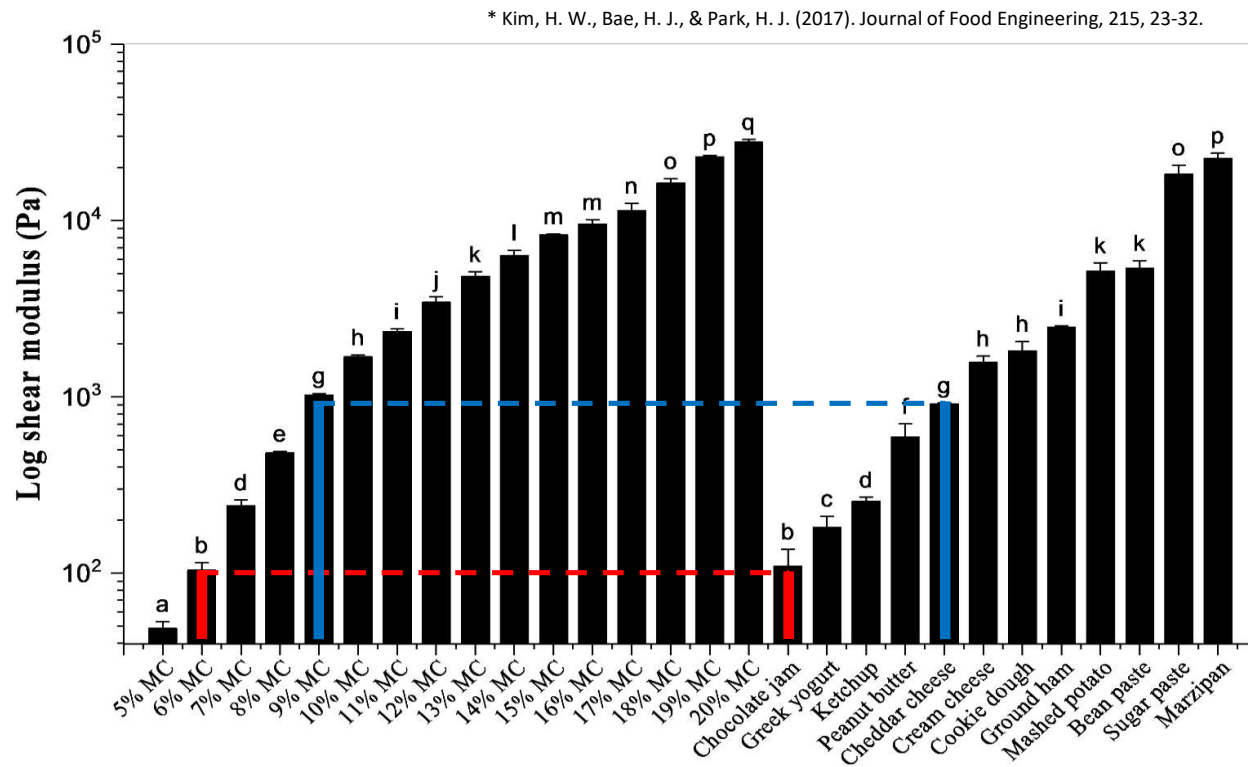


Fig. The deformation rate of structure

Shear Modulus reflect Deformation Behavior

- The values of shear modulus of all samples were in complete agreement with dimensional stability.



*Rheometer

Classification of the Dimensional Stability

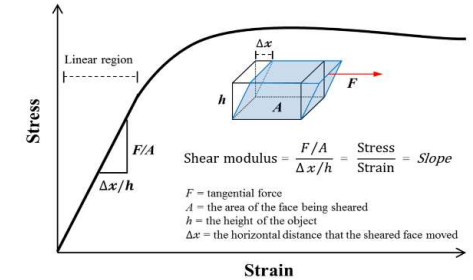


Table. The classification of the dimensional stability

Classification	MC concentration (%)	Characteristics	Printable range	Application field	Rheological specifications (Pa)
A	> 12	Can be formed complex models with high height	Printable for height of 80 mm	Decoration of geometric structure	$> 5 \times 10^3$
B	11-12	Can be formed simple models with high height	Printable for height of 40 mm	Plate divider multiple height filled	$2-5 \times 10^3$
C	9-10	Can be formed simple models with low height	Printable for height of 20 mm	Custom cookies	$0.5-2 \times 10^3$
D	< 9	Impossible to form 3D structures	Printable for 2D printing	Plate decoration	$< 5 \times 10^2$

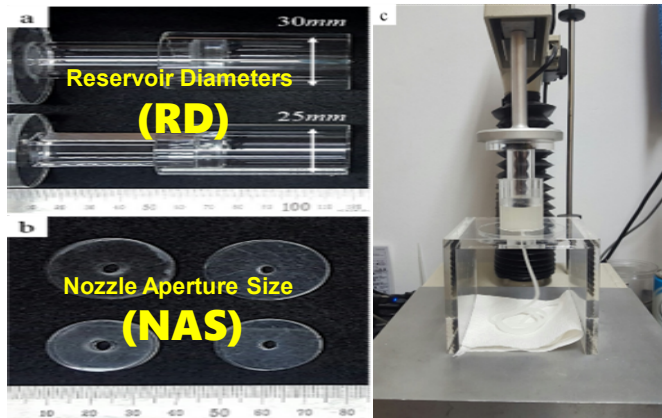
Shear Modulus

* Kim, H. W., Bae, H. J., & Park, H. J. (2017). Journal of Food Engineering, 215, 23-32.

- This system was categorized to grade according to the **capability in holding the shape.**
 - MC mixture with molecular weight of approximately 88,000 g/mol at 25 °C was set as standard

Extrudability Measurement

- The extrusion force increased with decreasing the nozzle aperture size (NAS) and increasing the reservoir diameter (RD).



NAS ↓ → Force ↑
RD ↑ → Force ↑

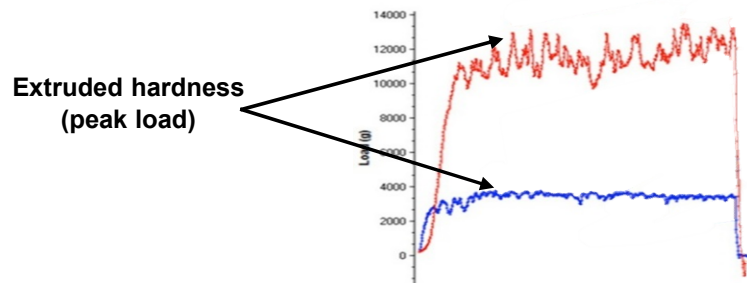


Table. The extrusion force of the reference material and foods

Samples	Extruded hardness (kg)		
	RD25NAS3	RD25NAS4	RD30NAS4
<i>MC mixtures (%)</i>			
5	1.92 ± 0.68 ^c	1.60 ± 0.35 ^{ab}	1.64 ± 0.08 ^b
6	3.01 ± 0.06 ^d	2.05 ± 0.16 ^{bc}	3.22 ± 0.28 ^c
7	4.36 ± 0.37 ^e	3.24 ± 0.04 ^{cd}	5.58 ± 0.38 ^d
8	6.21 ± 0.14 ^f	4.45 ± 0.50 ^{de}	7.09 ± 0.16 ^e
9	7.17 ± 0.55 ^f	4.88 ± 0.34 ^e	9.51 ± 0.10 ^{fg}
10	9.54 ± 0.30 ^g	6.89 ± 0.65 ^f	10.64 ± 0.60 ^g
11	11.06 ± 0.43 ^h	7.93 ± 0.23 ^f	12.18 ± 0.13 ^h
12	13.75 ± 0.55 ⁱ	10.23 ± 0.63 ^g	15.47 ± 0.24 ⁱ
13	14.48 ± 0.68 ⁱ	11.46 ± 1.16 ^g	18.51 ± 0.19 ^j
14	16.93 ± 0.44 ^j	13.52 ± 0.72 ^h	20.57 ± 0.64 ^k
15	18.48 ± 0.76 ^k	14.30 ± 0.26 ^h	21.70 ± 0.86 ^k
16	20.41 ± 0.75 ^l	16.36 ± 0.84 ⁱ	24.63 ± 1.94 ^l
17	22.21 ± 0.08 ^m	17.52 ± 0.41 ⁱ	27.15 ± 1.13 ^m
18	25.92 ± 0.73 ⁿ	22.21 ± 0.53 ^k	30.96 ± 0.44 ⁿ
19	29.22 ± 0.56 ^o	24.00 ± 0.82 ^o	34.00 ± 0.82 ^o
20	33.09 ± 2.60 ^p	26.07 ± 1.09 ^l	37.42 ± 0.41 ^p
<i>Experimental foods</i>			
Ketchup	0.06 ± 0.01 ^a	0.02 ± 0.01 ^a	0.06 ± 0.01 ^a
Greek yogurt	0.06 ± 0.02 ^a	0.04 ± 0.02 ^a	0.05 ± 0.00 ^a
Cream cheese	0.60 ± 0.01 ^{ab}	0.53 ± 0.01 ^a	0.96 ± 0.17 ^{ab}
Mashed potato	1.30 ± 0.07 ^{bc}	1.06 ± 0.05 ^{ab}	1.44 ± 0.09 ^b
Chocolate jam	1.40 ± 0.13 ^{bc}	0.81 ± 0.04 ^b	1.57 ± 0.50 ^b
Ground ham	1.43 ± 0.05 ^{bc}	0.97 ± 0.06 ^{ab}	1.62 ± 0.03 ^b
Peanut butter	1.69 ± 0.02 ^{bc}	1.02 ± 0.06 ^{ab}	1.46 ± 0.09 ^b
Bean paste	4.61 ± 0.50 ^e	3.11 ± 0.17 ^c	4.53 ± 0.10 ^d
Cheddar cheese	6.40 ± 0.73 ^f	4.88 ± 0.54 ^e	9.03 ± 1.08 ^f
Cookie dough	18.95 ± 0.69 ^k	14.07 ± 1.28 ^h	33.85 ± 2.36 ^o
Marzipan	55.33 ± 0.46 ^q	34.66 ± 2.78 ^m	—
Sugar paste	—	54.97 ± 1.02 ⁿ	—

Classification of the Extrudability

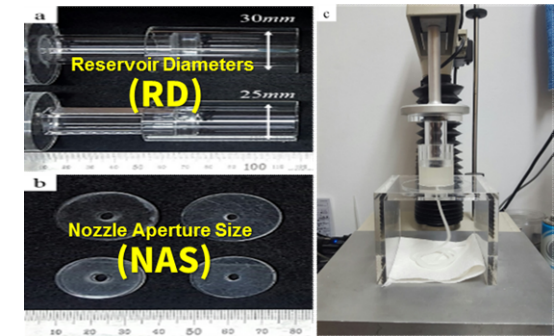


Table. The classification of the extrudability

Classification	MC concentration (%)	Handling properties (Extrudability)	Characteristics	Samples	Mechanical specifications (kg)
A	< 6	Easy to extrude	Available for sophisticated 3D object	Cream cheese, Chocolate jam	> 3
B	6-10	Can be extruded normally	Applicable for general printing system	Cheddar cheese, Bean paste	3-10
C	11-15	Difficult to extrude	Requires high output extruder for printing	Cookie dough	10-20
D	> 15	Extremely difficult to extrude	Requires melting to promote flowability	Sugar paste, Marzipan	< 20

* Kim, H. W., Bae, H. J., & Park, H. J. (2017). Journal of Food Engineering, 215, 23-32.

- The grade system was **applied in the same manner** as the classification of dimensional stability.
- **RD of 25 mm, NAS of 4 mm, and compression rate of 1 mm/s as a standard condition.**

Printability coding system

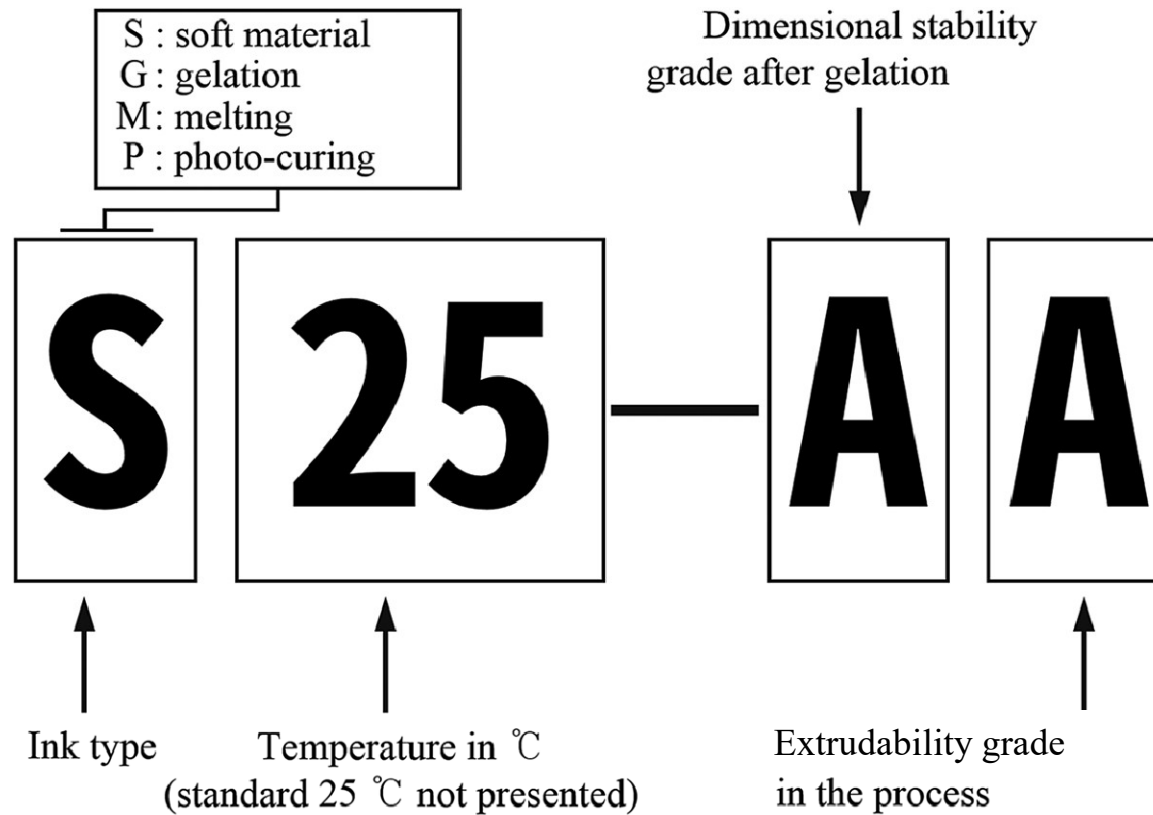


Fig. Printability coding system for FDM 3D printing fields.

「 **Finding 2** 」

Techniques of Food Material Texturization

Problems in formulating materials

- Most vegetables are known as non-printable traditional food materials.

* Procedia Manufacturing, Volume 1, 2015, Pages 308–319

Interacting Factors

High water content
Low carbohydrate
Low fat and protein
Low adhesiveness

Difficulties get over by



Gelling
Self supporting
Agglomerating
Solidifying



**Poor Resolution
and Printability**



* Solid Freeform Fabrication Symposium (pp. 809-815).



* The International Conference on Design and Technology, KEG, pages 23–29.

“An ink-system that the particle is dispersed in a gel matrix”



Interacting Factors

- **Vegetable powder**

- Source (Constituent)
- Particle rheology
- Particle size
- Volume fraction
- Swelling properties

- **Gelled matrix**

- Gel type
- Gel strength
- Concentration
- Water holding capacity

- **Mixture or ‘ink’**

- Viscoelastic (G , G')
- Yield stress
- Cohesiveness
- Adhesiveness
- Extrudability
- Flexibility

Effect of Water Holding Capacity on Printing Performance

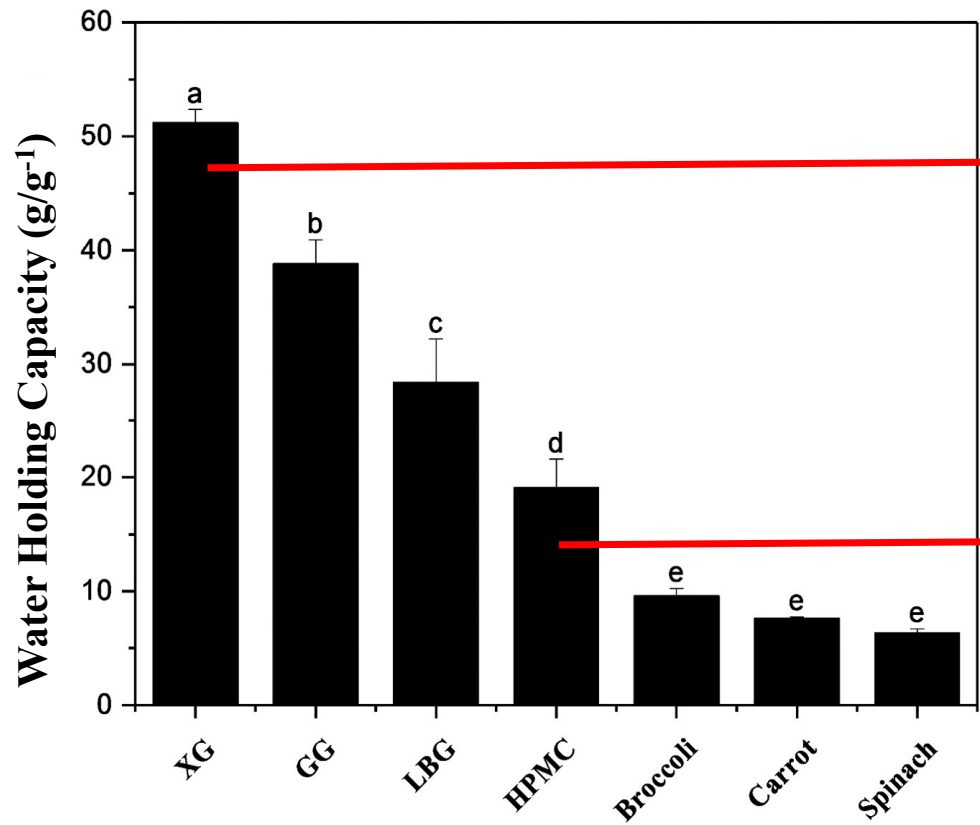
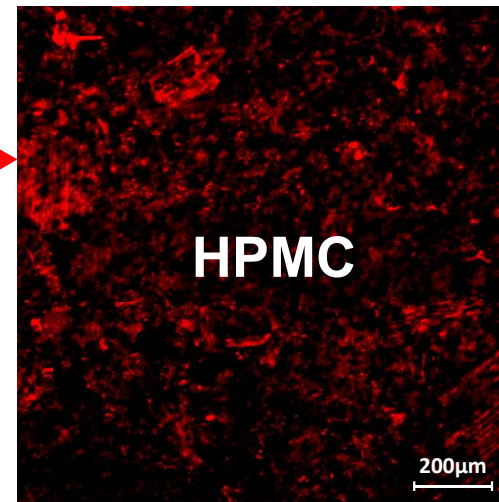
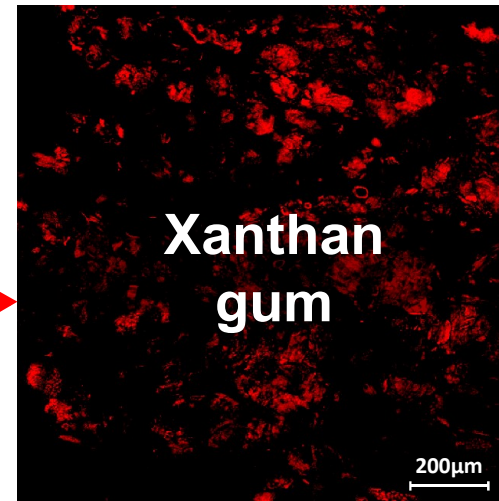
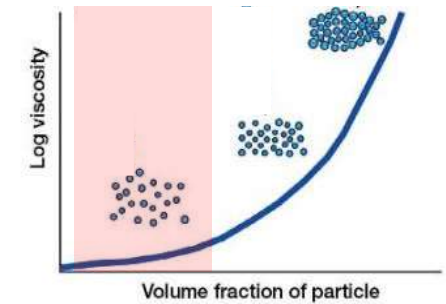


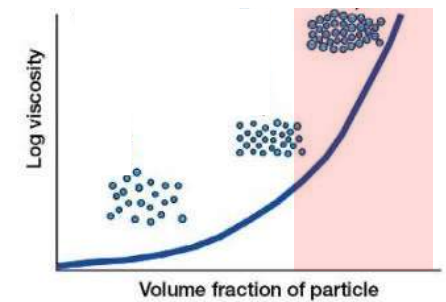
Fig. WHC of the hydrocolloids and vegetable samples.



Suppress the swelling
of vegetable particles



Completely swollen



The effects of hydrocolloids on printing performance

● HPMC

- For the HPMC matrix, there is a **significant differences** in rheological values(G' , G'') among the vegetable sources.
- The relatively low WHC of HPMC was insufficient to inhibit the swelling of the vegetable powder.

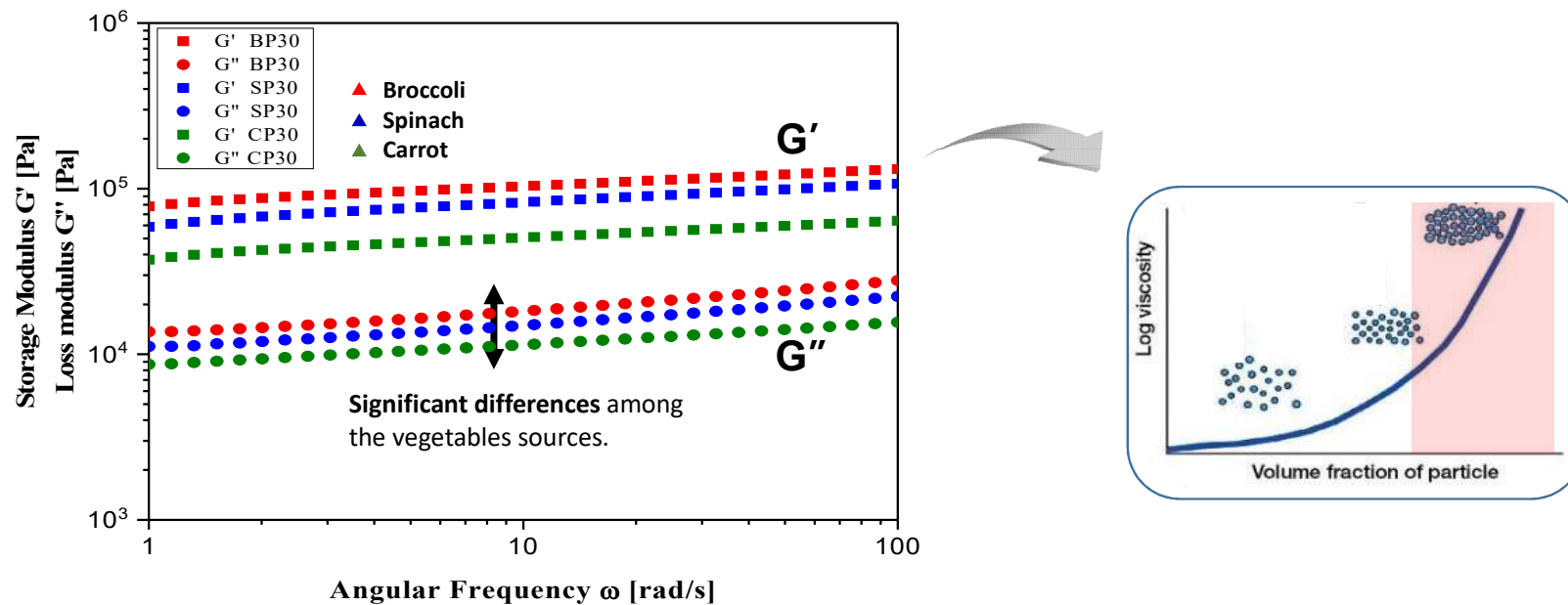


Fig. G' and G'' for 30% vegetable mixture with low WHC hydrogel

The effects of hydrocolloids on printing performance

● Xanthan Gum

- XG-based mixtures showed **the least difference between the viscoelastic values** of the different vegetables.

→ XG, which has a very high WHC, could **inhibit the swelling** of the powders to an extreme degree.

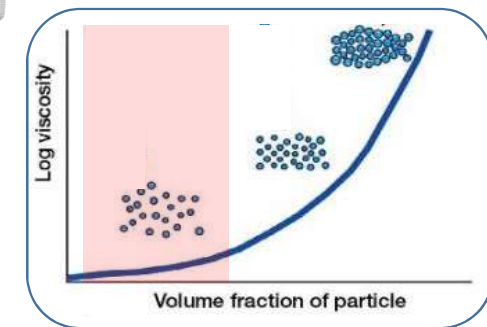
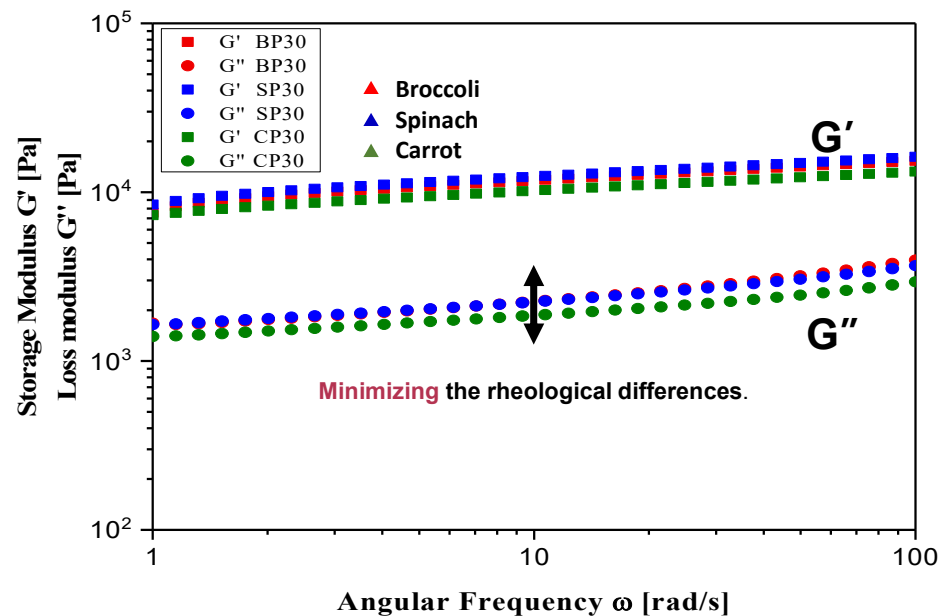


Fig. G' and G'' for 30% vegetable mixture with high WHC hydrogel

The Printing Performance of Vegetable-inks

- Vegetable particles in mixture with HPMC were completely swollen.
 - The products could withstand the structure, but **showed poor printing performance.**
- XG with high WHC (Water Holding Capacity) can sufficiently inhibit the swelling of vegetable particles.
 - The mixtures using **hydrocolloid with high WHC** displayed a fine resolution.

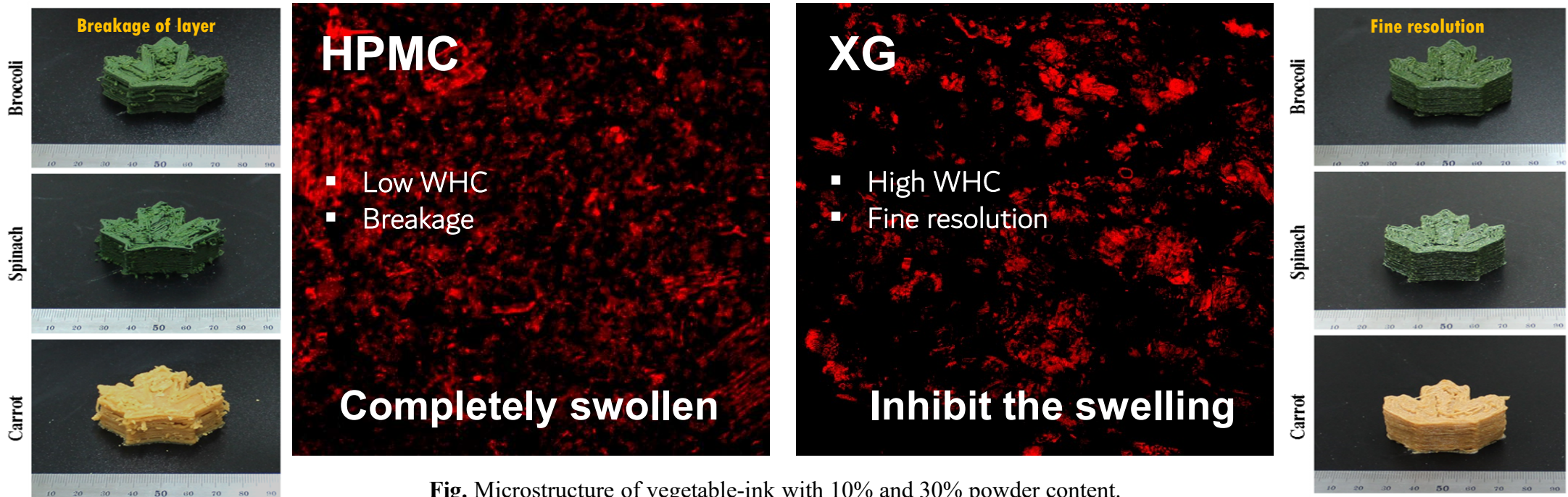


Fig. Microstructure of vegetable-ink with 10% and 30% powder content.

「 Finding 3 」

**Effect of particle size
on 3D printing performance**

Effect of particle size on 3D printing performance

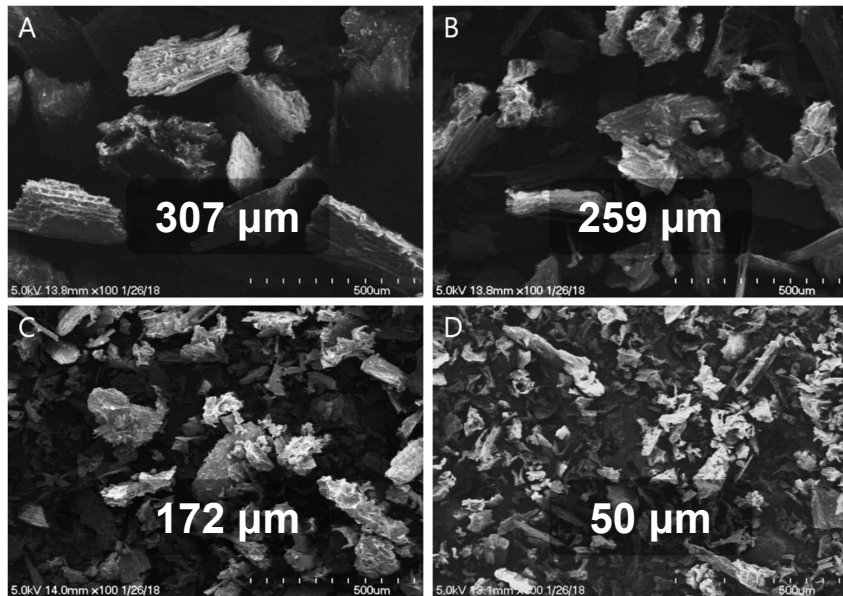


Fig. SEM images for spinach powder samples. Particle size: 307 μm (A), 259 μm (B), 172 μm (C) and 50 μm (D).

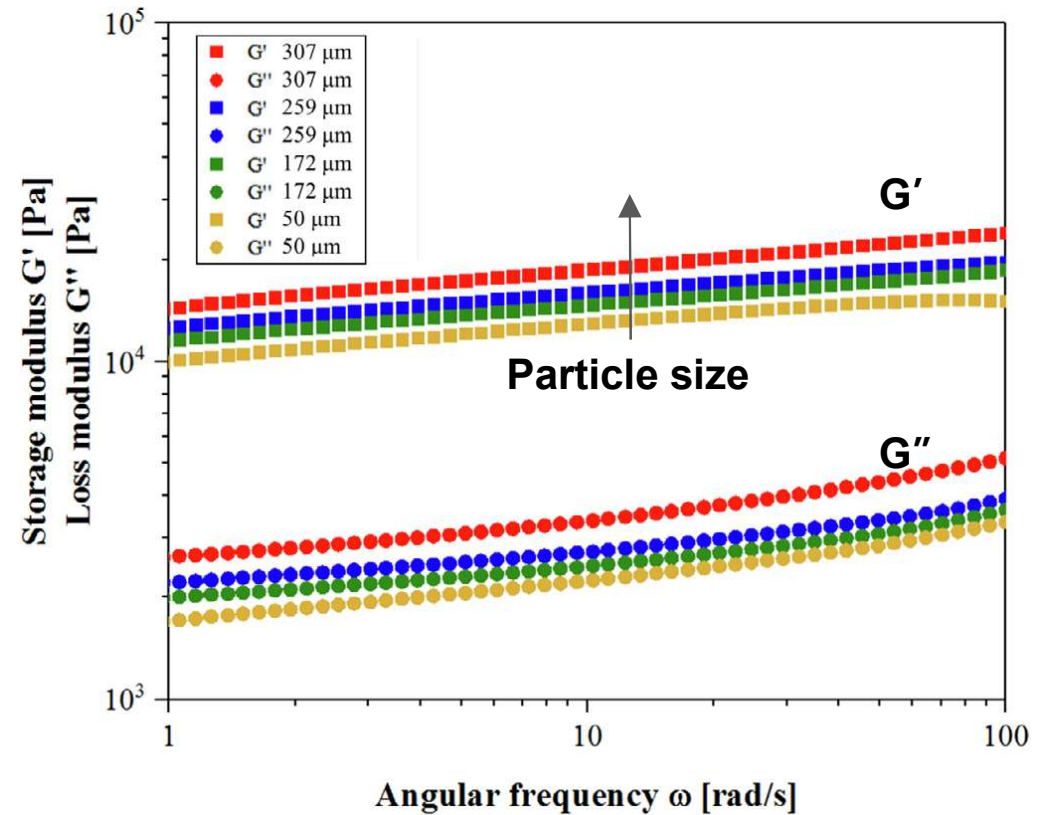
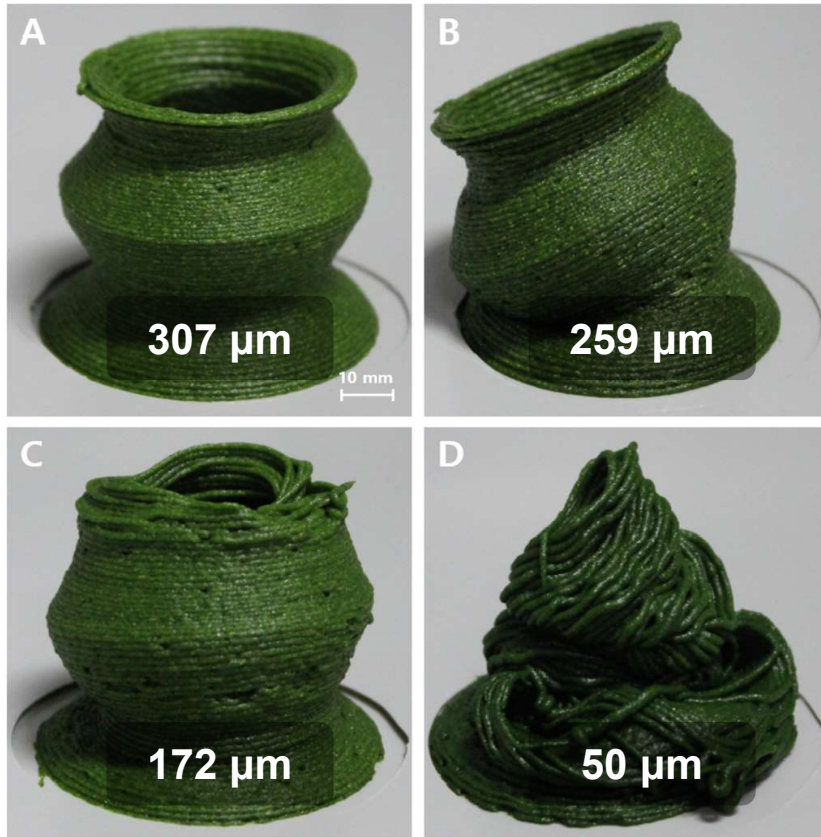


Fig. 2. Storage modulus (G') and loss modulus (G'') versus angular frequency (ω) for spinach dispersion with particle sizes of 307 μm (A), 259 μm (B), 172 μm (C) and 50 μm (D).

Effect of particle size on 3D printing performance



- A larger particle size promoted shape stability during the printing process.
- The particle size can be considered for the 3D Food printing.
- This may be useful in determining parameters which required to prepare the food-ink such as the milling time.

Particle size

Increase

Obtain efficient dimensional stability

Fig. Images of 3D printed spinach dispersions with various particle sizes of 307 μm (A), 259 μm (B), 172 μm (C) and 50 μm (D).

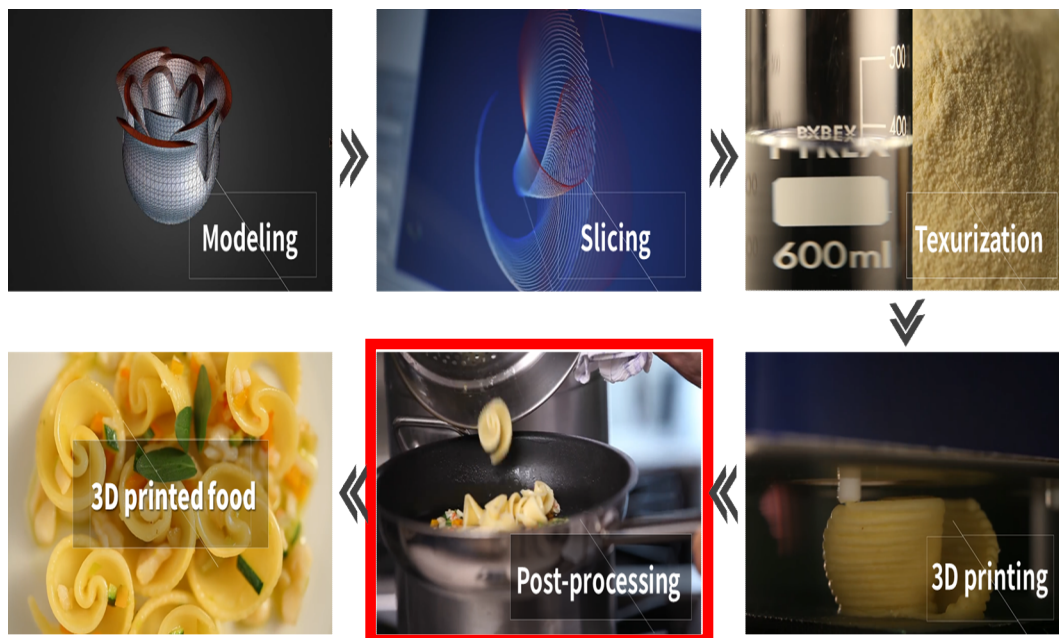
「 **Finding 4** 」

Post-processing

Conventional post-processing

3D printing step

- Properties of food material after the post-processing such as cooking have not been extensively studied.



* such as cooking

J.I. Lipton et al. / Trends in Food Science & Technology 43 (2015) 114e123 119



Figure 1: Common cookie recipes are printable(a), but the printed geometries do not survive backing(b).

- Significant deformation of the products during post-processing.

Temperature-sweep dynamic shear profile

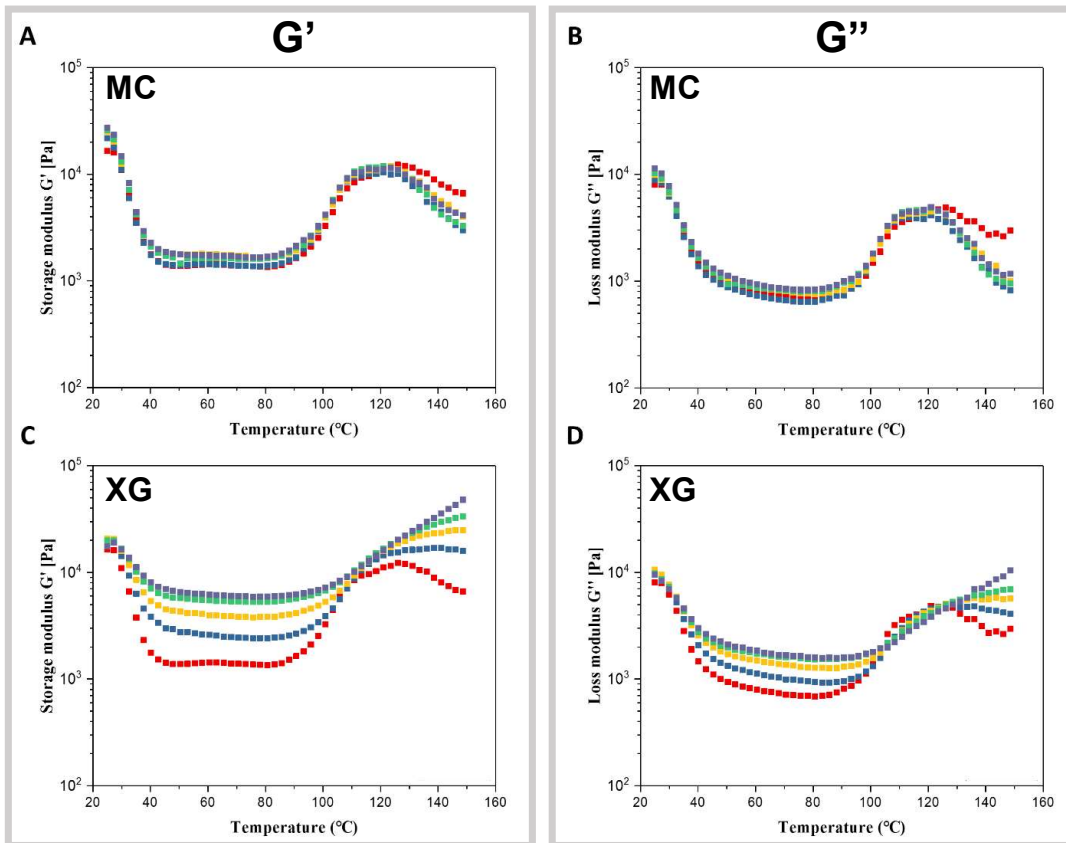


Fig. 1. Storage modulus (G') and loss modulus (G'') versus temperature ($^{\circ}\text{C}$) for cookie dough with (A and B) methylcellulose and (C and D) xanthan gum. Incorporation level: (■) control, (■) 0.5 g/100 g, (■) 1 g/100 g, (■) 2 g/100 g and (■) 3 g/100 g.

- **A remarkable drop** in G' and G'' values at 40°C .
- **Methylcellulose**
 - Gel point of approximately 48.5°C
 - No significant increase in G' and G''
 - inhibited by the fatty acids and proteins
- **Xanthan Gum**
 - Enhancing effect
 - Resist deformation over a wide temp

➔ **The concentration of XG increase, G' and G'' of XG also increase**

3D printing and post-processing

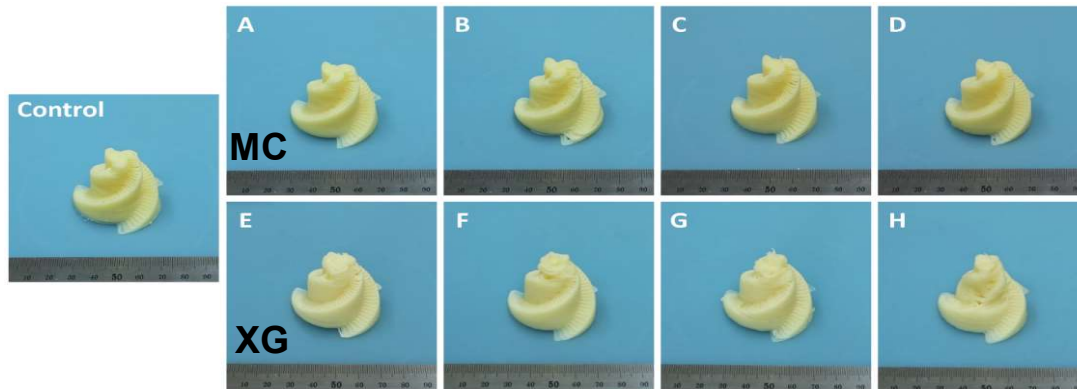


Fig. The objects printed using cookie dough with addition of methylcellulose and xanthan gum

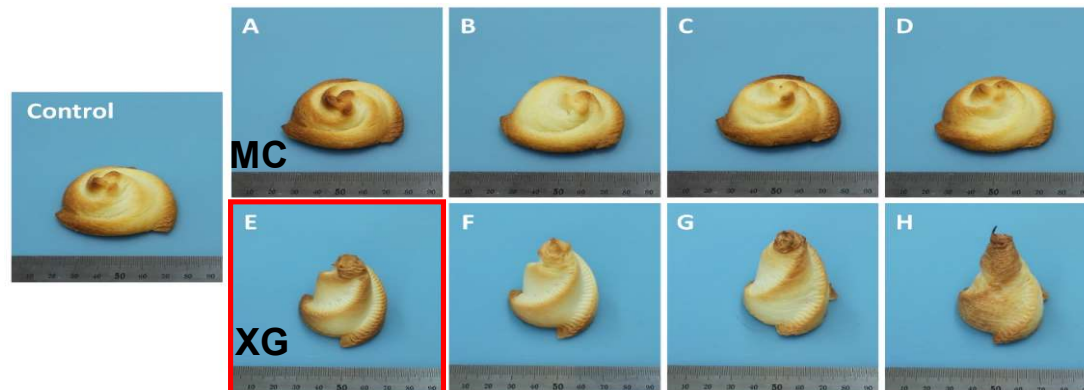


Fig. The effect of post-processing on appearance of 3D printed cookies

▪ Methyl Cellulose (MC)

- Increase in MC concentration
- Printing : shape retention
- Post-processing : deformation

▪ Xanthan Gum (XG)

- Increase in XG concentration
- Printing : shape retention
- Post-processing : shape retention



Xanthan Gum

prevents deformation after heating

「 **Finding 5** 」

3D printing-based cell culture

Callus Based Food-Ink

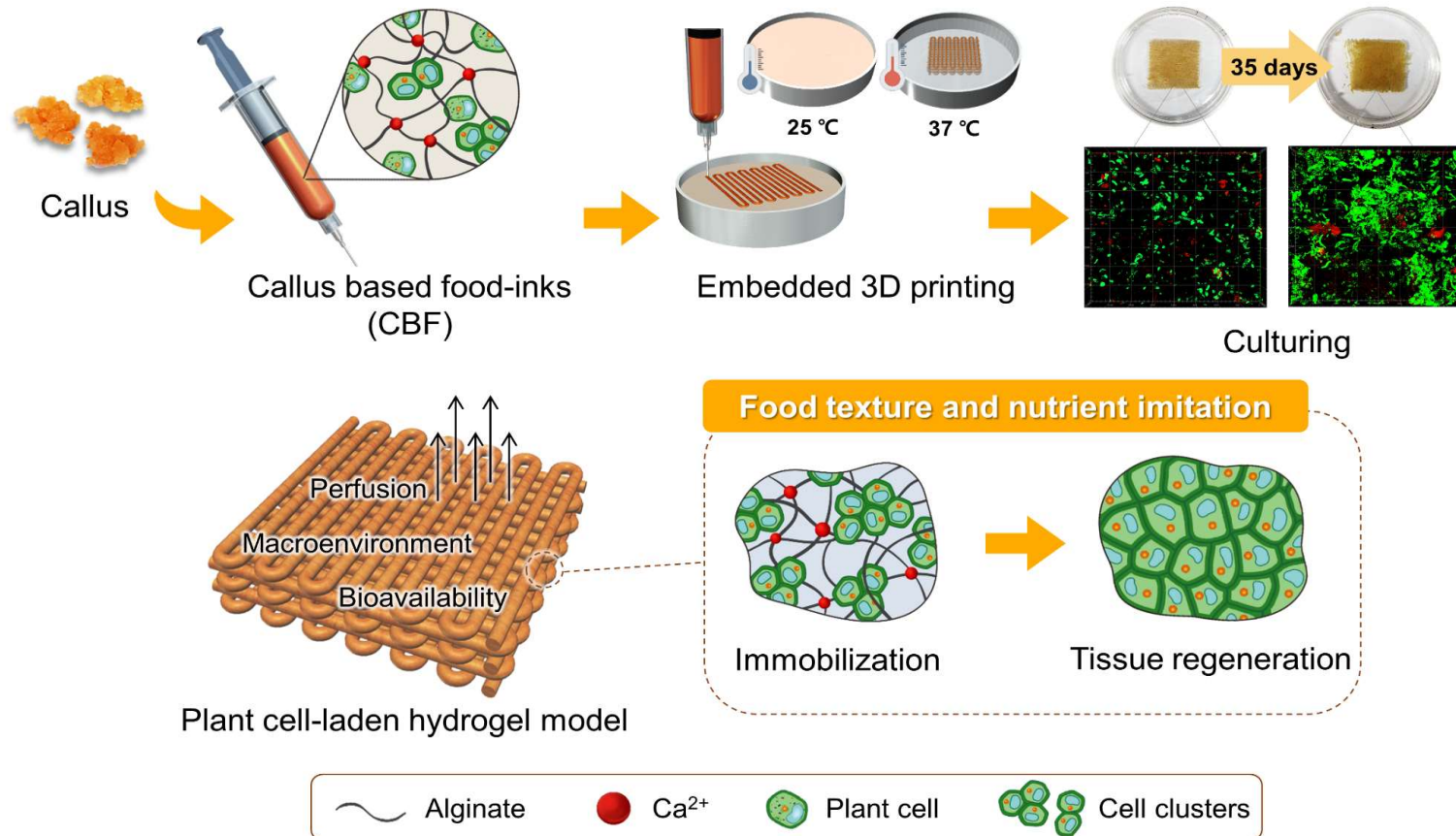


Fig. Plant cell-laden hydrogel model with predefined geometric specificity through integration of 3D printing and plant cell culture technologies.

Fabrication of 3D lattice scaffold

- The printing was performed in gelatin thermoreversible bath containing CaCl_2 .
- Callus samples dispersed in alginate were well-adhered.

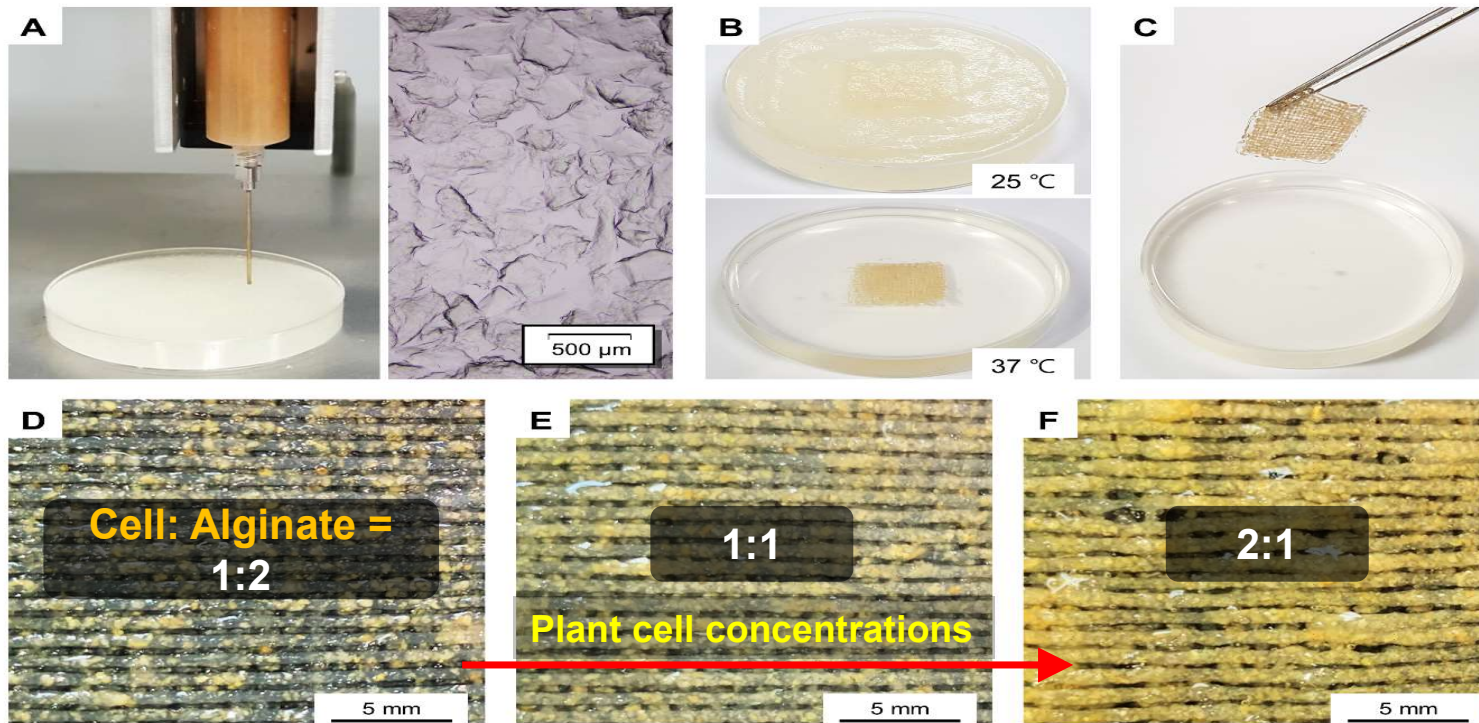
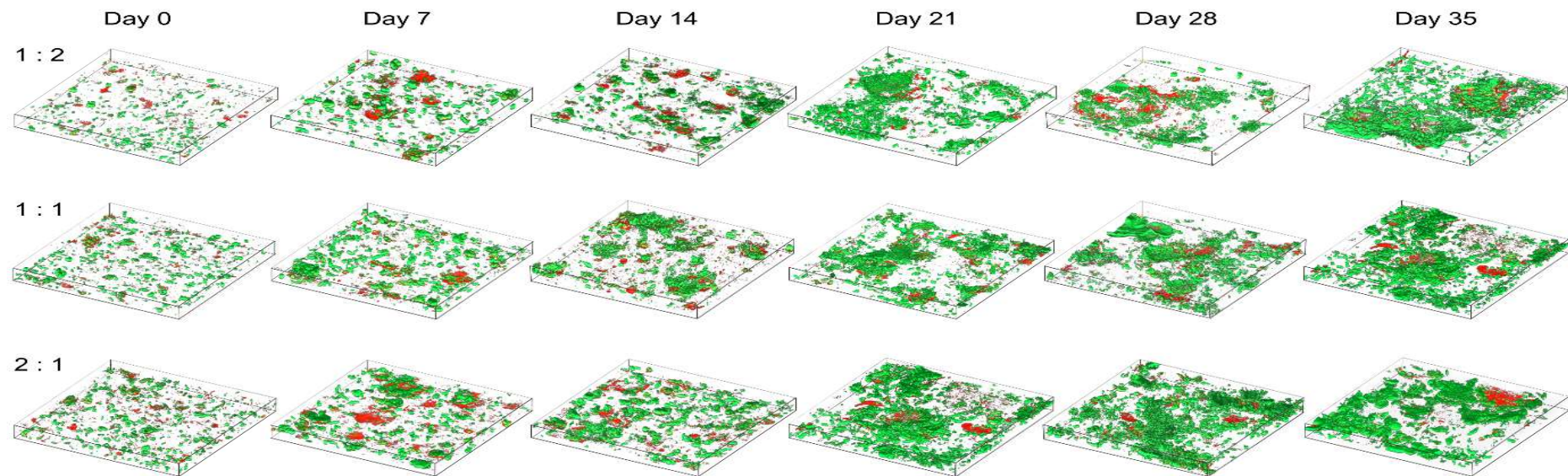


Fig. Printing process (A - C) and printability of CBB samples with the ratio of 1:2 (D), 1:1 (E) and 2:1 (F) using FRESH technique.

Cell proliferation within cell-loaded CBF gels

- The initial cell concentration did not affect the final cell volume.
- However, cell clusters did not develop into a rigid tissue.



- Live cells = **green**
- dead cells and cell debris = **red**.

Fig. 3D distribution of the carrot callus in the CBF hydrogels. Cells were separated into live cells (green) and dead cells (red) in a cuboidal volume of $300\ \mu\text{m} \times 2400\ \mu\text{m} \times 2400\ \mu\text{m}$. Cell viability was observed for 5 weeks at an interval of one week.

Mechanical characteristics during incubation

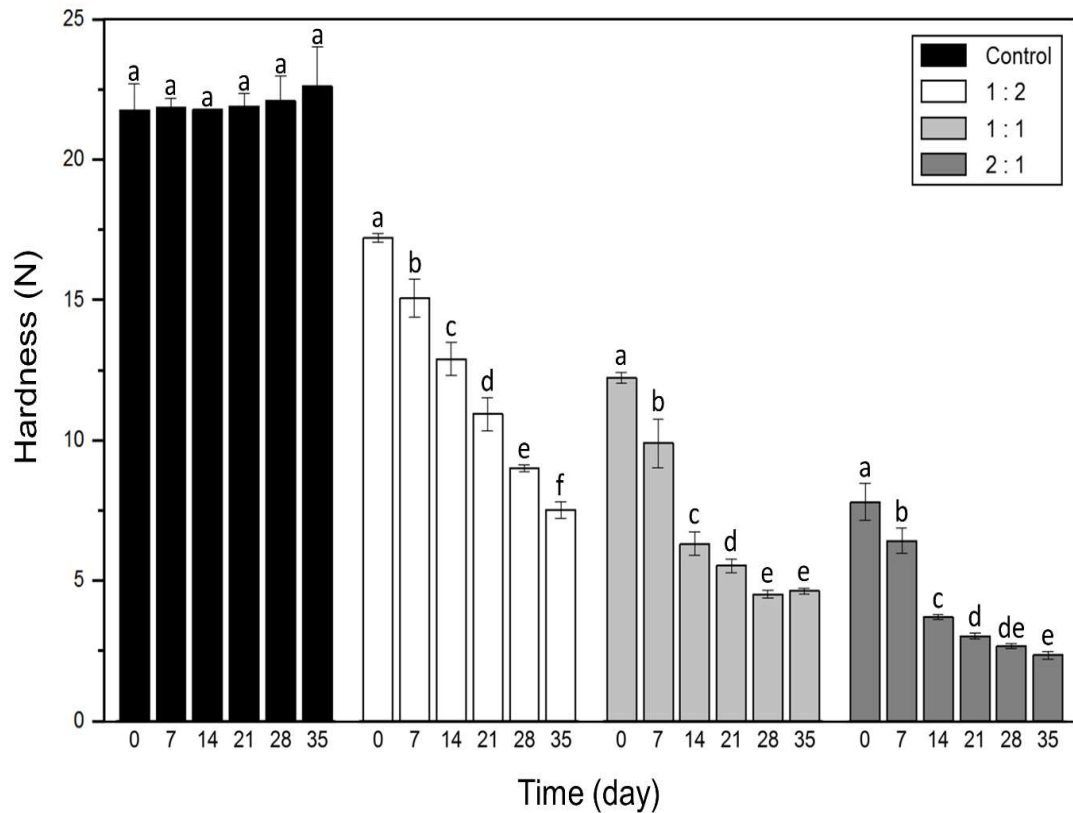


Fig. Mechanical gel strength of the CBF (Callus based- food ink) gels while culturing for 35 days.

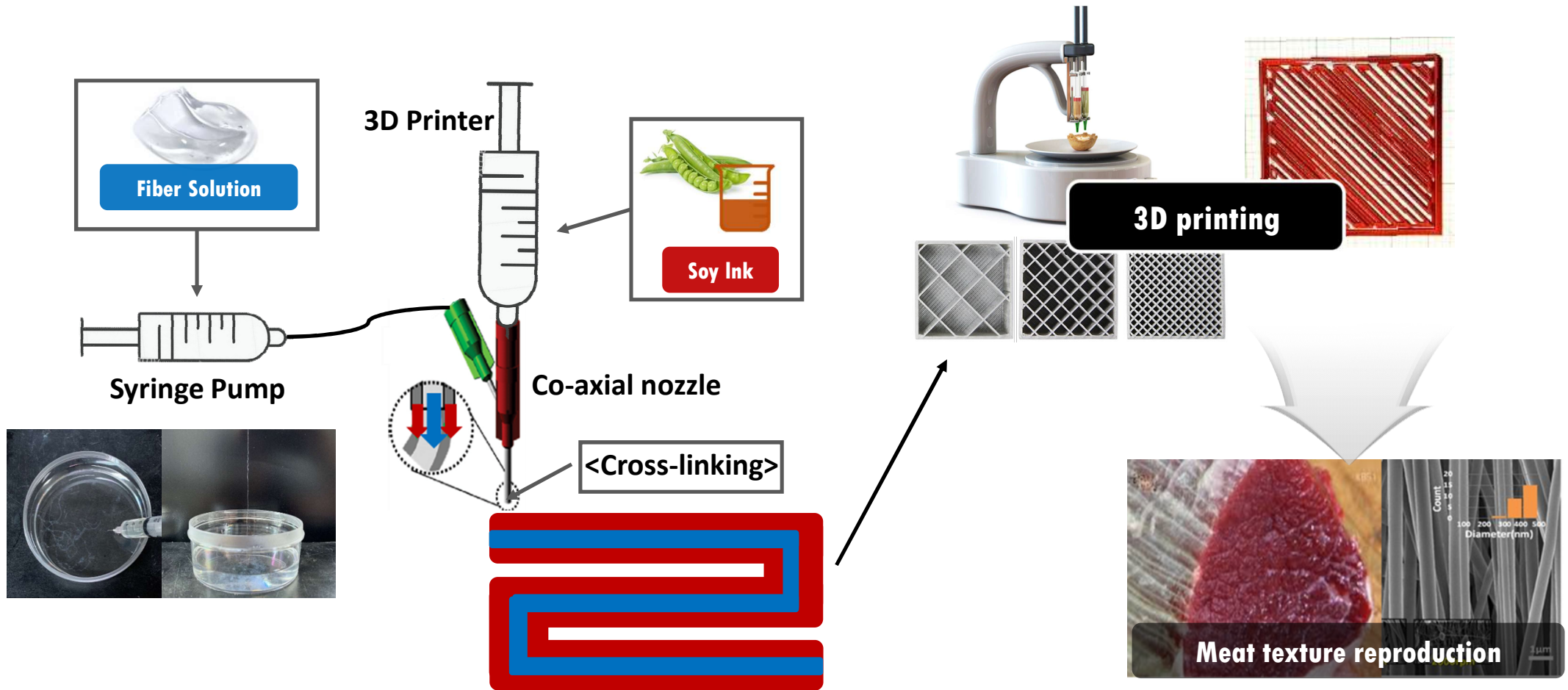
- The mechanical properties of the CBF gel decreased as the cell growth increased.
- In order to make real carrot-like products, the mechanical strength of the CBF gel through cell proliferation needs to be improved in a near future.

「 On going project 」

Plant-based meat substitute

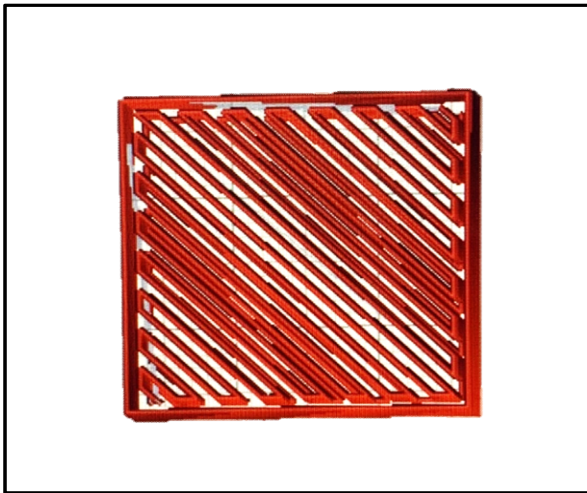
Development of plant based meat using co-axial nozzle

- Coaxial nozzle with dual inks system (fiber ink and soy ink) can generate meat fiber-like structure.



Production of myofibrillar tissue by 3D printing

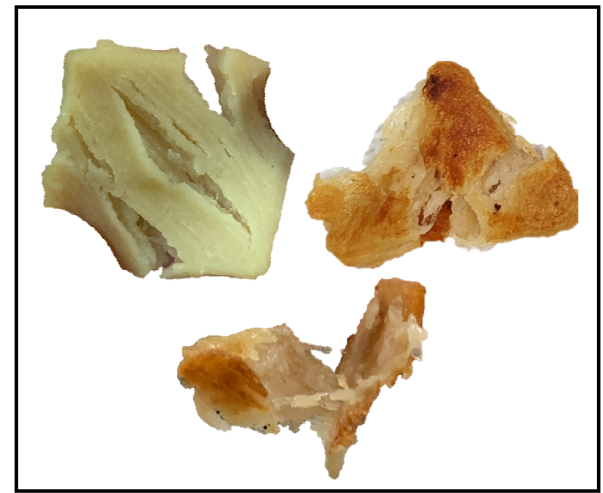
- We generate meat fiber-like structure **after cooking**.



[Modeling]



[Printing]



[Post-processing, Cooking]

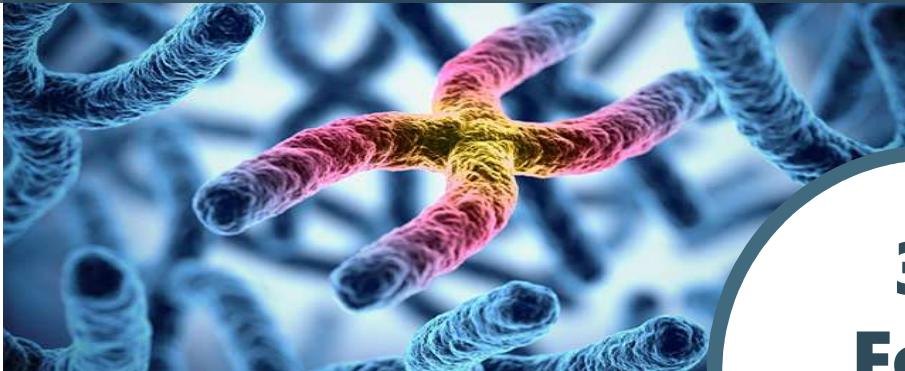
03

CHAPTER

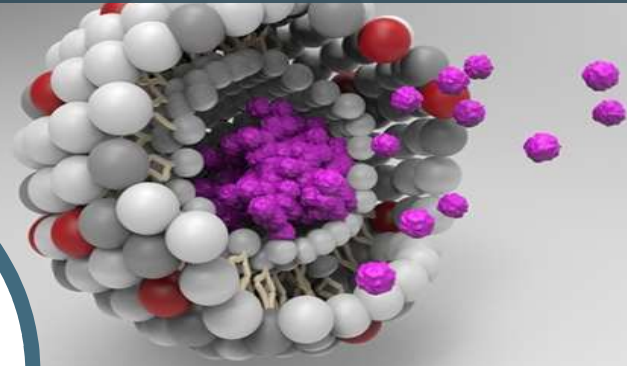
Future Direction

Application field

Genome-Based Personalized Food



Nano-technology



3D Food Printing

Alternative Meat



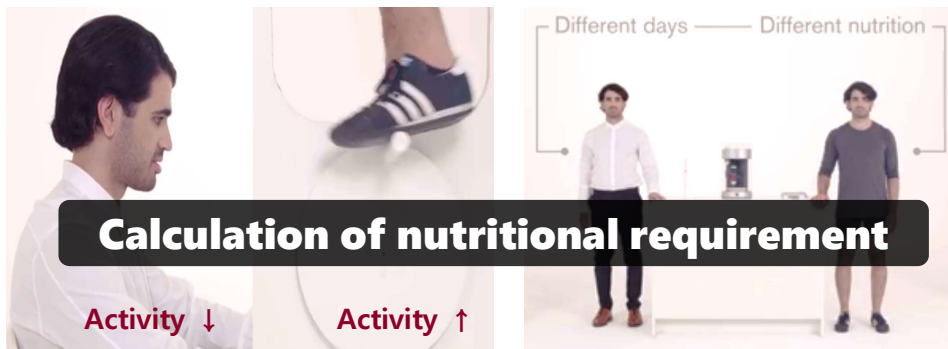
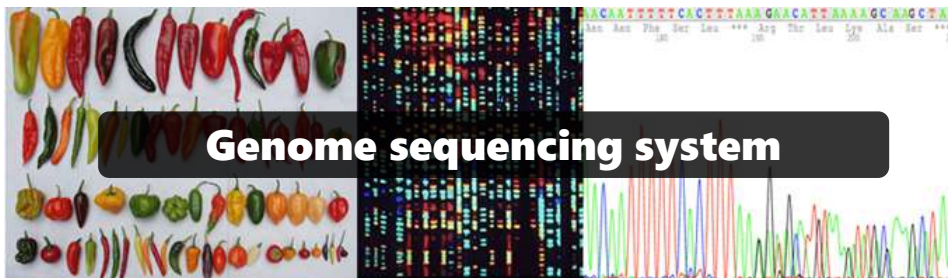
Elderly Food



Application field

■ Genome-based personalized food manufacturing

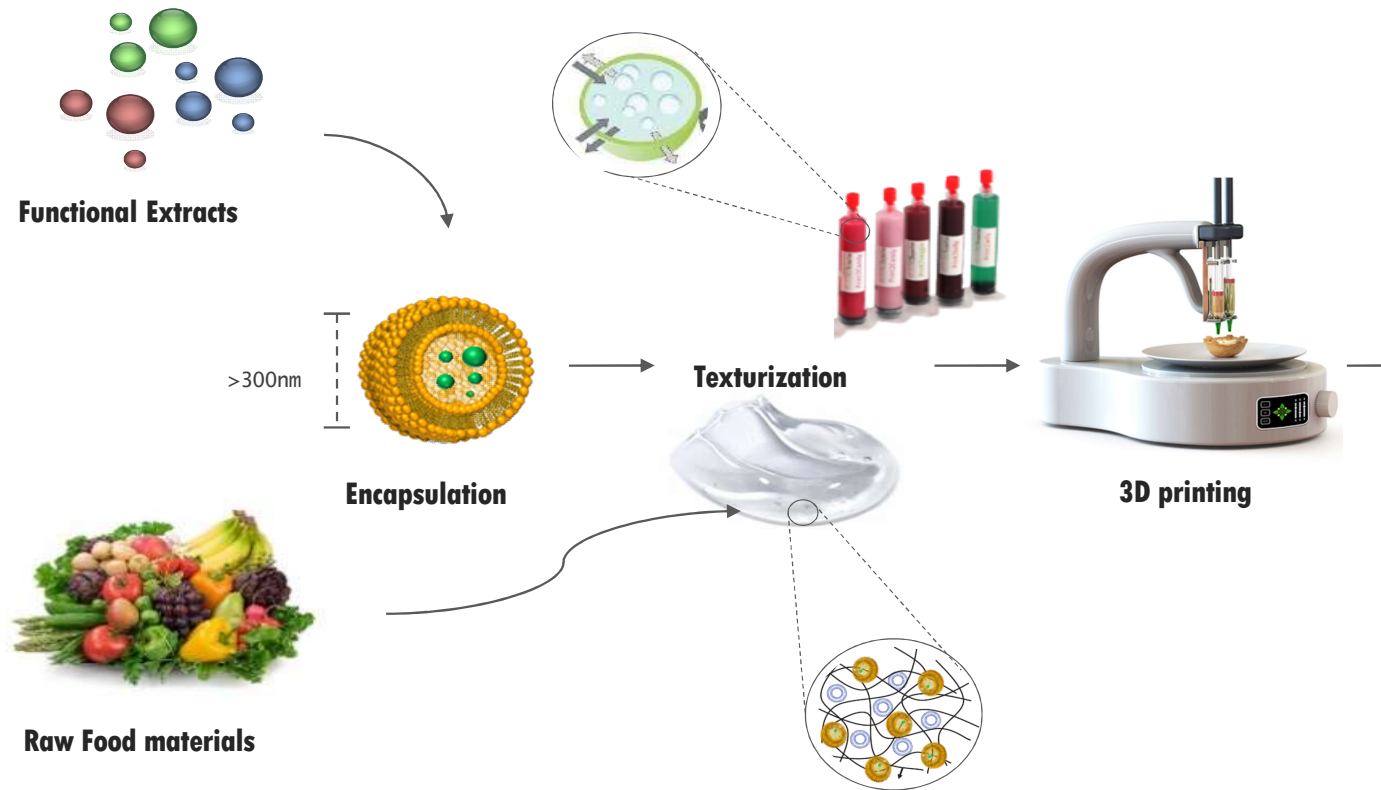
- Personalized food according to individual's metabolism level, disease.
- ICT convergence healthcare system.



▲ personalized food manufacturing

Application field

3D Printing with Nano-technology



All in One Food

315 Kcal	437 Kcal
15g Fat	20g Fat
25.3 Carbs	50.7 Carbs
5.8mg V.D	376mg V.C

personalized nutrition



Taste, flavor



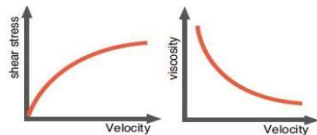
Texture modification

Application field

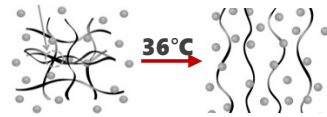
Multifunctional food

1 Chewing and swallowing

- Texture control based on hydrocolloids



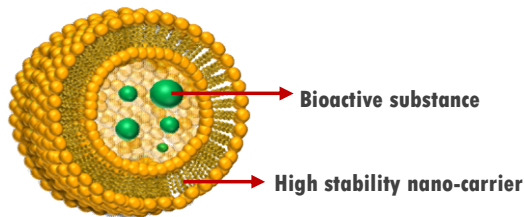
[Pseudoplastic]



[Thermosensitive]

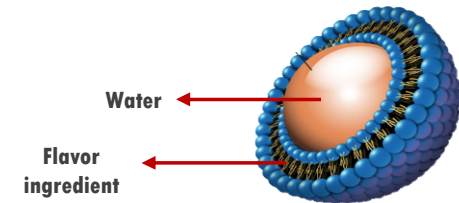
2 Function of physiology

- In vivo mass transfer technology



3 Function of sensory

- Maximize the efficiency of flavor components by surface area

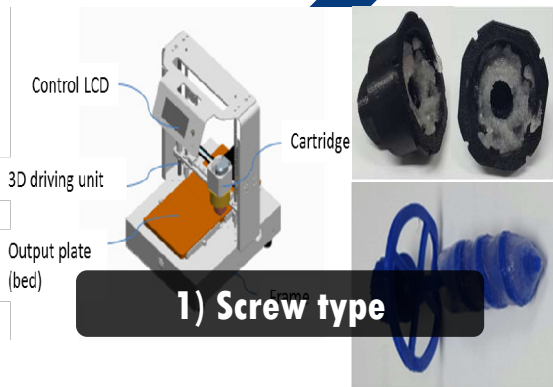
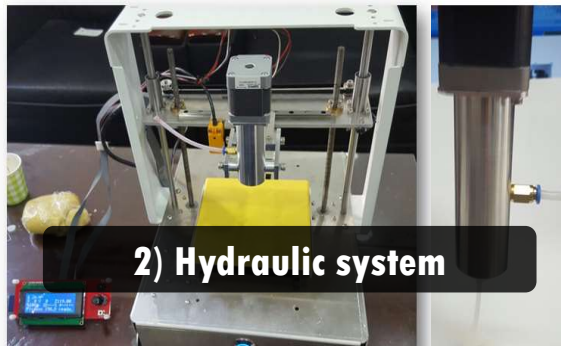


4 Personalization

- Personal nutrition customized system

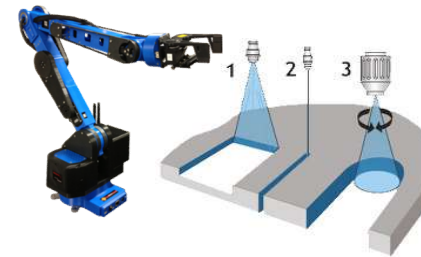
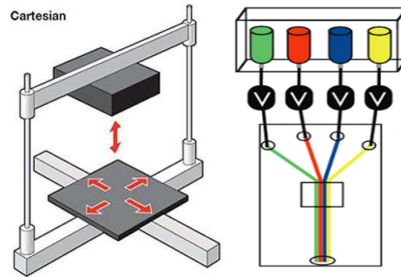
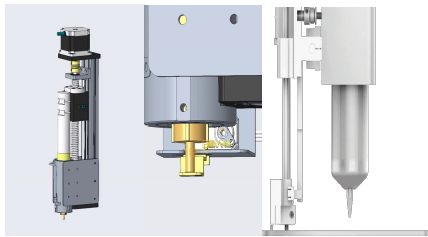


Equipment Development History in our Lab



Technology roadmap

Extrusion system



60 min

20~35 min

5~15 min

3~5 min

- Nozzle opening and closing
- Real-time control

- Multi-Nozzle Quantity Control
- Slicing algorithm

- 6-axis drive
- Adjustable nozzle system

- Induction heating
- Premix automatic mixing

2019

2020

2021

2023

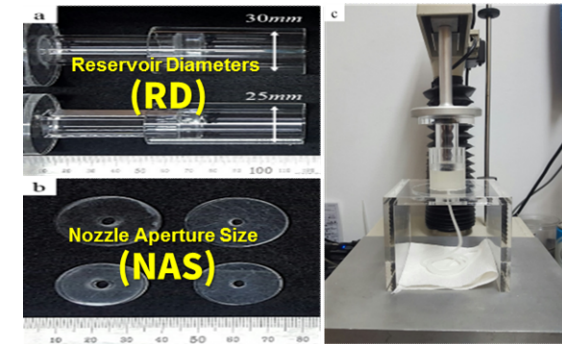
Speed (100g)

Technology

Standardization of Equipment

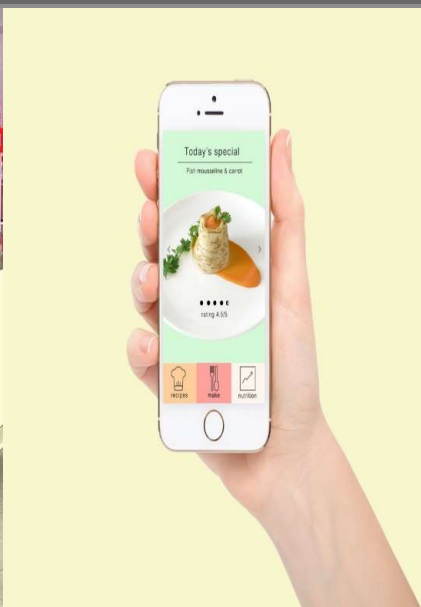
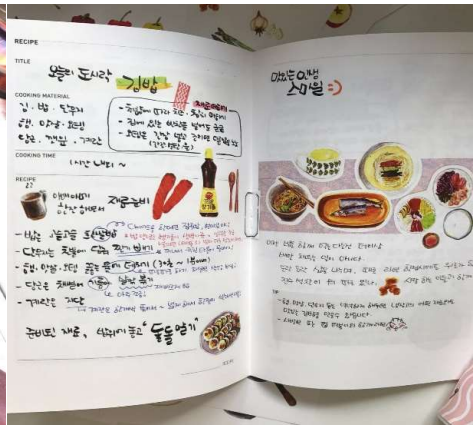
“There is no standard for 3D food printer equipment ”

- Unqualified printers are misused



Key elements

- **Cartridge**
 - Reservoir capacity
 - Reservoir morphology
 - Nozzle aperture size
- **3D printer**
 - Nozzle moving speed
 - Extrusion force
 - Accuracy
 - Ease of Use
- **Standardization**
 - Use of Standards
 - Leveling



[2019] 3D Food Printing Symposium in Korea

행사 당일 촬영 후 삽입



Thank You

