WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

FDC
FROZEN DESSERT CENTER

Non-dairy frozen desserts and their microstructure

Didem Sözeri Atik, Ph.D.

Postdoctoral Researcher in Hartel Lab, Department of Food Science, University of Wisconsin-Madison, USA

Assistant Professor, Department of Food Engineering, Tekirdağ Namık Kemal University, Turkey

Outline

- Introduction about non-dairy frozen desserts
- Materials
- Results
  - Composition
  - Rheological behavior
  - Fat destabilization
  - Ice crystal size
  - Air cell size
  - Meltdown
- Conclusion

Plant-based foods

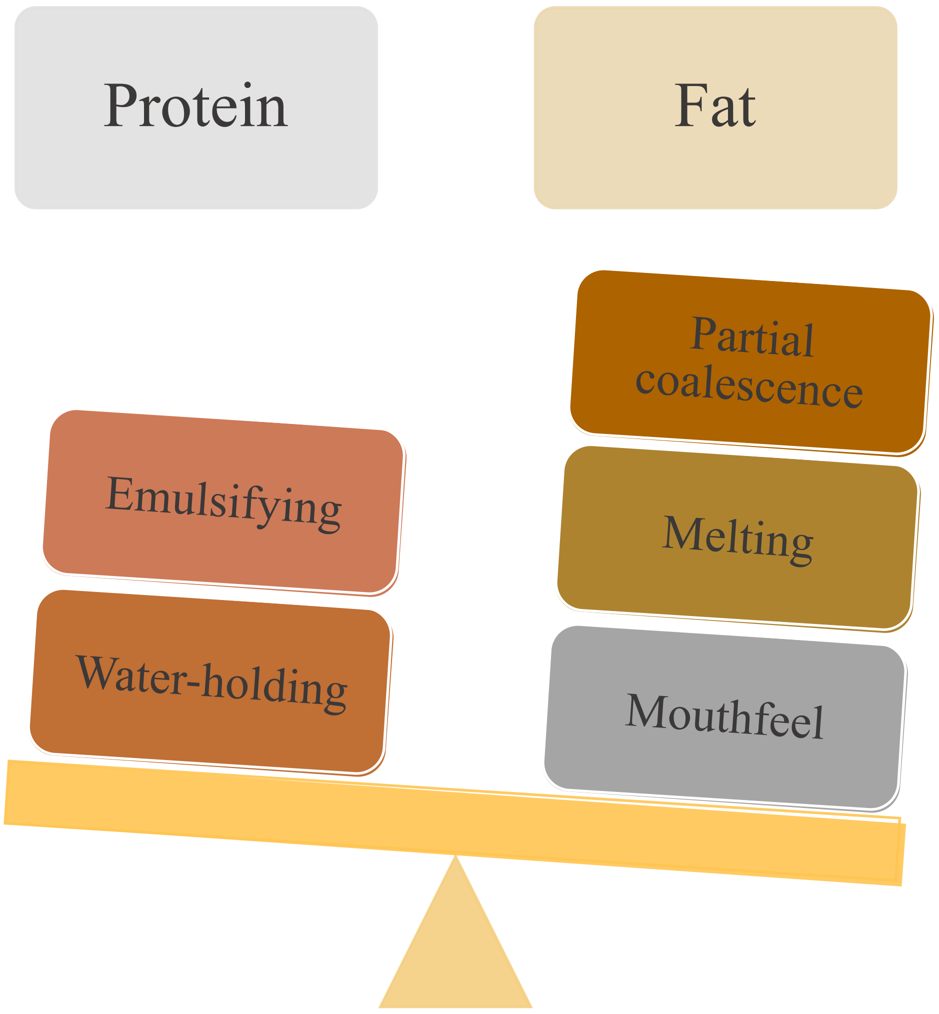
- Increasing **global consumer interest** in the adoption of a plant-based diet
  - Health, sustainability, and ethics
- Considerable **economic success**
  - Milk and meat alternatives produced from plant sources
- Meet the **preferences** and **standards** of consumers
  - Presented significant difficulties
- The main reason is the **complex composition** and **structure** of the original products
  - Reproducing these attributes using plant-based components

Non-dairy frozen desserts

- The term Plant-based or non-dairy frozen desserts
  - Does not contain **dairy, eggs, or any other products derived from animals**
- The production process is similar to dairy ice cream
  - But the **components are different**
- Future Market Insights, 2023
  - Increasing demand among **young individuals** in developed countries
  - The market value of them is expected to reach **US$ 4.3 billion by 2033**.

Why is it hard?

- Replacing the **functional properties** of milk-based components with their **plant-based alternatives** is challenging
  - Protein
  - Fat
- Unique characteristics of milk protein and fat
- Create colors, textures, and flavors that are similar to those of ice cream



Purpose of the research

- Several factors can affect the **structural properties of** non-dairy frozen desserts
- The interactions between them **are not well understood**
- A comprehensive study on **commercial** non-dairy frozen desserts **has not been documented**
- Understand and evaluate **without any controlled parameters**
    - Rheological
    - Structural
    - Melting properties

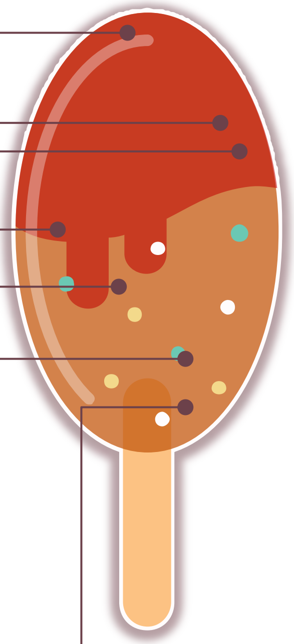
- Properties of plant-proteins
- Fat sources
- Process conditions
- Other ingredients (emulsifiers, stabilizers, and etc)

Materials

- **15 vanilla non-dairy** frozen dessert samples
- **Three containers** of each product were purchased
- Numbered **randomly**
- One **limitation** of the samples
  - Formulations, processing, and storage conditions prior to purchase were **unknown**
- Stored in a **hardening freezer** at -28.9 C
- Analyses were conducted in **triplicate**

Methods

- Total solids, total fat, and protein, density
- Overrun, freezing point
- Rheological properties
- Fat destabilization
- Air cell size distribution
- Ice crystal size distribution
- Meltdown



Composition of commercial non-dairy frozen desserts

- Pea protein
- Oat milk
- Coconut milk

- Coconut oil
- Sunflower oil
- A mixture of coconut oil and one liquid oil

Protein source	%
Soy (Tofu, milk, protein)	13
Almond (Milk, almonds)	13
Oat (Milk, Flour)	27
Pea Protein	33
Cashew (Milk)	13
Coconut (Cream, milk)	20
Lupin Protein (Isolate)	7
Non-animal Whey Protein (Non-animal milk)	7

Fat Source	%
Corn oil	7
Cocoa butter	7
Safflower oil	7
Sunflower oil	20
Coconut (milk, oil or cream)	80
Soybean oil	7
Tocopherols	7
Low erucic rapeseed oil	7

Composition of commercial non-dairy frozen desserts

- The variability in results can be attributed to the **diverse composition** of individual product
- Variance in **processing parameters**
  - Dasher speed,
  - type of freezer,
  - storage conditions
- Samples with **high total solids** were also found to have a **lower freezing point** and **high fat content**
- Direct effect of **sweeteners on freezing point**

Sample code	Total solids (%)	Density (g/ml)	Total fat (%)	Protein (%)	Overrun (%)	Freezing point (°C)
540	42.20 ± 0.20^{a}	1.07 ± 0.0008^{g}	18.60	<2	82.25 ± 0.15^{a}	-3.34 ± 0.03^{f}
381	35.68 ± 0.52^{ef}	1.11 ± 0.002^{b}	6.10	1	77.85 ± 0.39^{b}	-2.75 ± 0.01^{cd}
900	35.85 ± 0.56^{ef}	1.09 ± 0.002^{de}	9.50	1	64.98 ± 0.37^{h}	-2.32 ± 0.10^{a}
767	37.16 ± 0.73^{cde}	1.09 ± 0.003^{def}	10.80	<1	69.69 ± 0.50^{de}	-2.93 ± 0.11^{de}
516	35.49 ± 0.57^{ef}	1.12 ± 0.002^{a}	3.80	2	71.04 ± 0.40^{d}	-2.44 ± 0.11^{ab}
849	37.32 ± 0.53^{cde}	1.10 ± 0.002^{bc}	8.70	2	68.27 ± 0.36^{ef}	-2.61 ± 0.09^{bc}
732	40.39 ± 0.90^{ab}	1.09 ± 0.004^{d}	13.00	1	73.47 ± 0.63^{c}	-3.30 ± 0.12^{f}
465	32.06 ± 0.34^{g}	1.05 ± 0.001^{h}	14.00	2	67.04 ± 0.22^{fg}	-2.74 ± 0.07^{cd}
670	39.15 ± 0.44^{bc}	1.11 ± 0.002^{b}	8.80	1	55.88 ± 0.29^{j}	-2.91 ± 0.08^{de}
238	36.28 ± 0.60^{e}	1.08 ± 0.002^{f}	11.70	<1	66.75 ± 0.40^{g}	-2.25 ± 0.06^{a}
489	36.74 ± 0.56^{de}	1.09 ± 0.002^{def}	10.80	1	69.40 ± 0.38^{e}	-2.34 ± 0.03^{ab}
800	38.75 ± 0.79^{bcd}	1.07 ± 0.003^{g}	15.80	3	49.16 ± 0.47^{k}	-2.29 ± 0.05^{a}
533	36.63 ± 0.57^{e}	1.10 ± 0.002^{cd}	9.20	2	59.69 ± 0.37^{i}	-2.24 ± 0.12^{a}
364	39.55 ± 0.62^{b}	1.08 ± 0.002^{f}	14.40	1	54.69 ± 0.39^{j}	-3.17 ± 0.04^{ef}
510	33.97 ± 1.53^{fg}	1.09 ± 0.006^{ef}	9.50	1	81.02 ± 1.11^{a}	-2.74 ± 0.16^{cd}
Min	32.06 ± 0.34	1.05 ± 0.001	3.80	<1	49.16 ± 0.47	-3.34 ± 0.03
Max	42.20 ± 0.20	1.12 ± 0.002	18.60	3	82.25 ± 0.1	-2.24 ± 0.12
Mean	37.15 ± 2.56	1.09 ± 0.01	10.97 ± 3.77		67.41 ± 9.51	-2.69 ± 0.37

Composition of commercial non-dairy frozen desserts

- Protein content **lower than that of in the literature** (3-4%)
- Variation is **high for fat content**
- An **inverse** relationship between **the density of the mix and fat content** is observed

Sample code	Total solids (%)	Density (g/ml)	Total fat (%)	Protein (%)	Overrun (%)	Freezing point (°C)
540	42.20 ± 0.20^{a}	1.07 ± 0.0008^{g}	18.60	<2	82.25 ± 0.15^{a}	-3.34 ± 0.03^{f}
381	35.68 ± 0.52^{ef}	1.11 ± 0.002^{b}	6.10	1	77.85 ± 0.39^{b}	-2.75 ± 0.01^{cd}
900	35.85 ± 0.56^{ef}	1.09 ± 0.002^{de}	9.50	1	64.98 ± 0.37^{h}	-2.32 ± 0.10^{a}
767	37.16 ± 0.73^{cde}	1.09 ± 0.003^{def}	10.80	<1	69.69 ± 0.50^{de}	-2.93 ± 0.11^{de}
516	35.49 ± 0.57^{ef}	1.12 ± 0.002^{a}	3.80	2	71.04 ± 0.40^{d}	-2.44 ± 0.11^{ab}
849	37.32 ± 0.53^{cde}	1.10 ± 0.002^{bc}	8.70	2	68.27 ± 0.36^{ef}	-2.61 ± 0.09^{bc}
732	40.39 ± 0.90^{ab}	1.09 ± 0.004^{d}	13.00	1	73.47 ± 0.63^{c}	-3.30 ± 0.12^{f}
465	32.06 ± 0.34^{g}	1.05 ± 0.001^{h}	14.00	2	67.04 ± 0.22^{fg}	-2.74 ± 0.07^{cd}
670	39.15 ± 0.44^{bc}	1.11 ± 0.002^{b}	8.80	1	55.88 ± 0.29^{j}	-2.91 ± 0.08^{de}
238	36.28 ± 0.60^{e}	1.08 ± 0.002^{f}	11.70	<1	66.75 ± 0.40^{g}	-2.25 ± 0.06^{a}
489	36.74 ± 0.56^{de}	1.09 ± 0.002^{def}	10.80	1	69.40 ± 0.38^{e}	-2.34 ± 0.03^{ab}
800	38.75 ± 0.79^{bcd}	1.07 ± 0.003^{g}	15.80	3	49.16 ± 0.47^{k}	-2.29 ± 0.05^{a}
533	36.63 ± 0.57^{e}	1.10 ± 0.002^{cd}	9.20	2	59.69 ± 0.37^{i}	-2.24 ± 0.12^{a}
364	39.55 ± 0.62^{b}	1.08 ± 0.002^{f}	14.40	1	54.69 ± 0.39^{j}	-3.17 ± 0.04^{ef}
510	33.97 ± 1.53^{fg}	1.09 ± 0.006^{ef}	9.50	1	81.02 ± 1.11^{a}	-2.74 ± 0.16^{cd}
Min	32.06 ± 0.34	1.05 ± 0.001	3.80	<1	49.16 ± 0.47	-3.34 ± 0.03
Max	42.20 ± 0.20	1.12 ± 0.002	18.60	3	82.25 ± 0.1	-2.24 ± 0.12
Mean	37.15 ± 2.56	1.09 ± 0.01	10.97 ± 3.77		67.41 ± 9.51	-2.69 ± 0.37

Rheological behavior

Viscosity

Important for

Proper whipping

Retention of air

Good body and texture

is affected by

Composition

Processing

Temperature

No ideal viscosity

High viscosity leads to an **increase in melting resistance** and a **smooth texture**

Low viscosity is for **rapid whipping** (fast freezing)

In the present research;

- Flow behavior
- Thixotropic (time-dependent) rheological behavior

Why is thixotropic behavior important?

- Ability to **recover their structure** during shear
- Evaluate the relationship between **structure and flow during the operation conditions** of the process.

Rheological behavior

- **Melted** frozen desserts are used
- A **wide range of values** in the rheological attributes
- **Non-Newtonian** behavior
- **Herschel Bulkley model** to explain the flow behavior
- A decrease in n values may lead to a **reduction in energy consumption during the mixing** of ice cream
- An increase in **viscosity or yield stress can help to resist melting**
- A higher **hysteresis area is the indicator of lower structural recoverability**
- A low area means the **highest recovery ability**.
- Can help to understand **important measurements** for non-dairy frozen dessert quality, such as
  - meltdown
  - texture

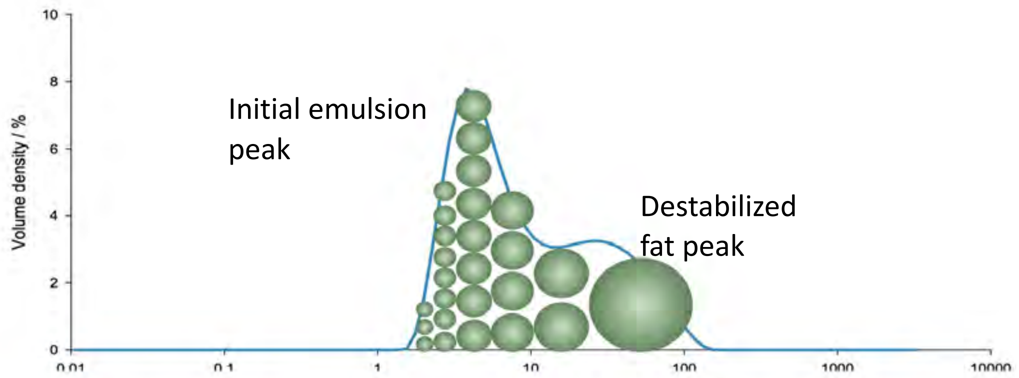
	Yield stress(Pa)	Consistency index (K, $Pa.s^n$)	Flow behavior index (n)	R-sq	Viscosity at 50 s^{-1}	Hysteresis loop (Pa/s)
Min	0.20±0.03	0.01±0.004	0.77±0.01	0.99	0.018±0.002	15.41±2.83
Max	28.57±4.36	1.51±0.25	1.43±0.24	0.99	1.614±0.070	1443.74±135.16
Mean of 15 samples	**4.05±7.20**	**0.50±0.41**	**0.90±0.18**		**0.357±0.383**	**199.01±353.74**

Partial coalescence/Fat destabilization

- Fat globule **size distribution**

$$\frac{Total\ percent\ volume\ of\ the\ destabilized\ fat\ clusters}{Total\ percent\ volume\ of\ the\ fat\ globules\ and\ clusters}$$

- **Controlled destabilization** of the emulsion is needed
- Develop an **internal structure** of agglomerated fat
  - Favorably alters the **texture and physical appearance**
  - Contributes to the **mechanical strength of the final pro**duct



Malvern, Panalytical, https://www.cif.iastate.edu/sites/default/files/uploads/Other_Inst/Particle%20Size/Particle%20Characterization%20Guide.pdf

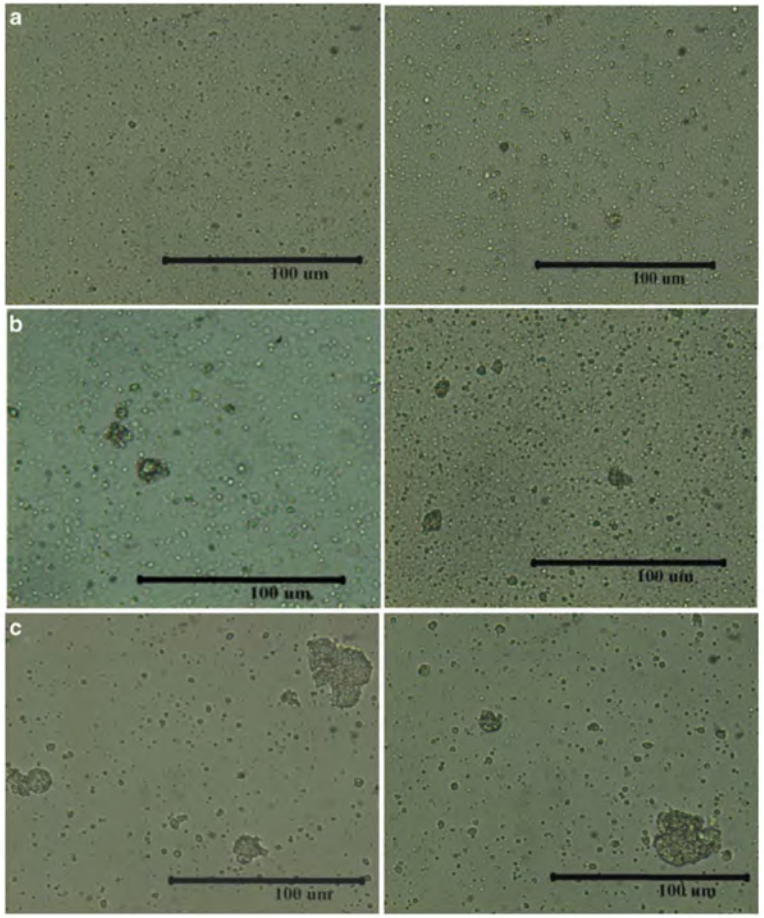
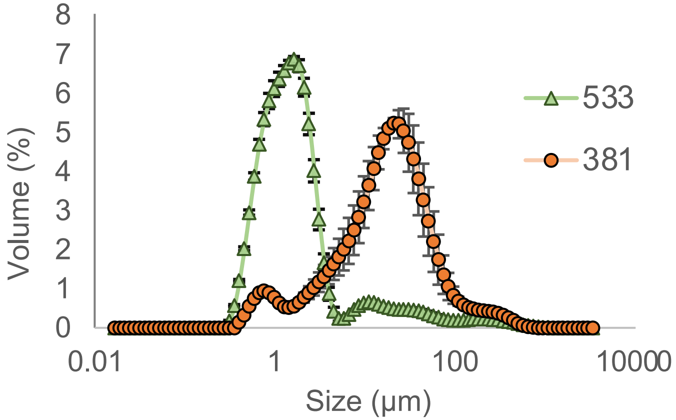


Fig. 11.10 Photomicrographs of fat globule clusters observed in melted ice cream. **(a)** Low level, **(b)** moderate level, and **(c)** high level of fat destabilization

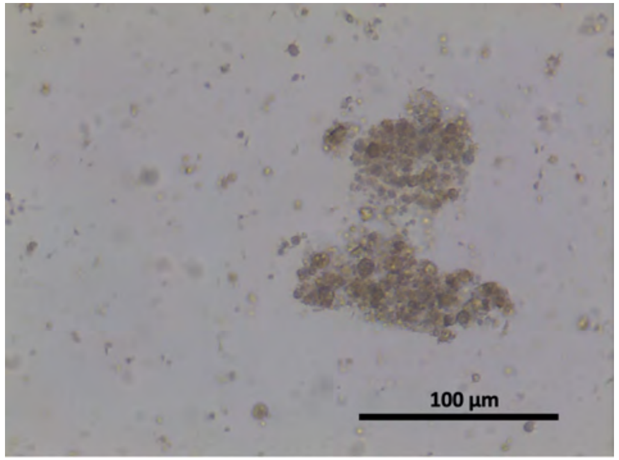
Goff, H. D., & Hartel, R. W. (2013). Ice cream, seventh edition. In *Ice Cream, Seventh Edition*. https://doi.org/10.1007/978-1-4614-6096-1

Partial coalescence/Fat destabilization

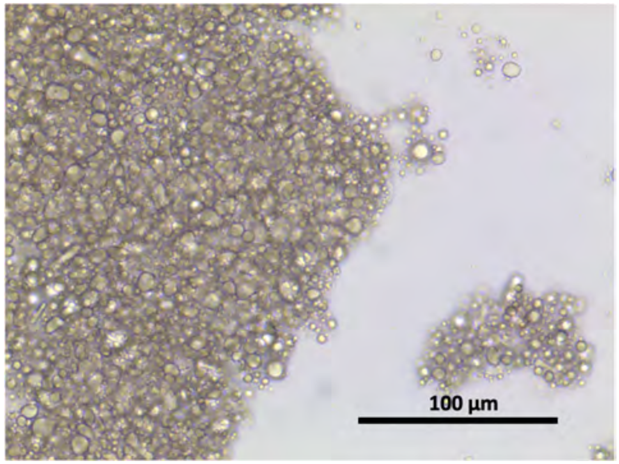
- **High overrun** leads to a **greater fat destabilization**
- **Higher viscosity** promotes fat destabilization
- Stabilizers, emulsifiers, and proteins have an effect
- **Increasing dasher speed** and **decreasing draw temperature** promotes fat destabilization by **enhancing the shearing effect**
- Depending **on the SFC**, the coalescence degree is changing
  - 364 and 767-coconut oil+sunflower oil
  - 381-safflower oil
  - 670-coconut oil



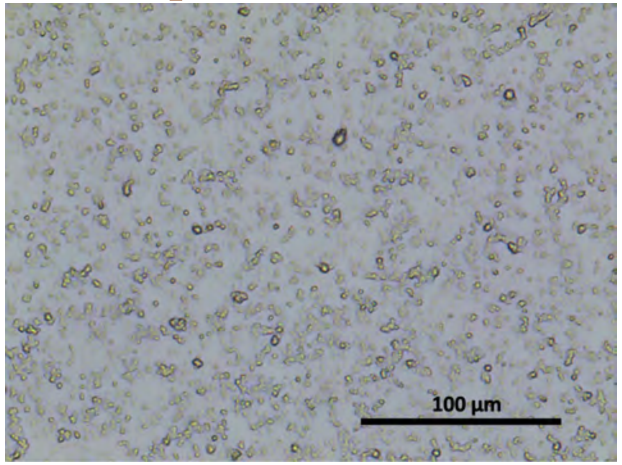
Sample 670- 86.28% FD



Sample 381- 93.01% FD



Sample 767- 3.60% FD



Samples	FD%
540	89.12±1.12[a]
381	93.01±0.64[a]
900	18.46±2.44[f]
767	3.60±1.16[g]
516	75.83±4.86[bc]
849	69.59±8.74[c]
732	89.43±0.86[a]
465	93.30±0.20[a]
670	86.28±0.79[ab]
238	31.95±0.80[e]
489	45.72±5.05[d]
800	90.71±1.70[a]
533	12.50±1.03[fg]
364	94.43±0.33[a]
510	36.25±6.86[de]
Min	3.60±1.16
Max	94.43±0.33
Mean	62.01±32.88

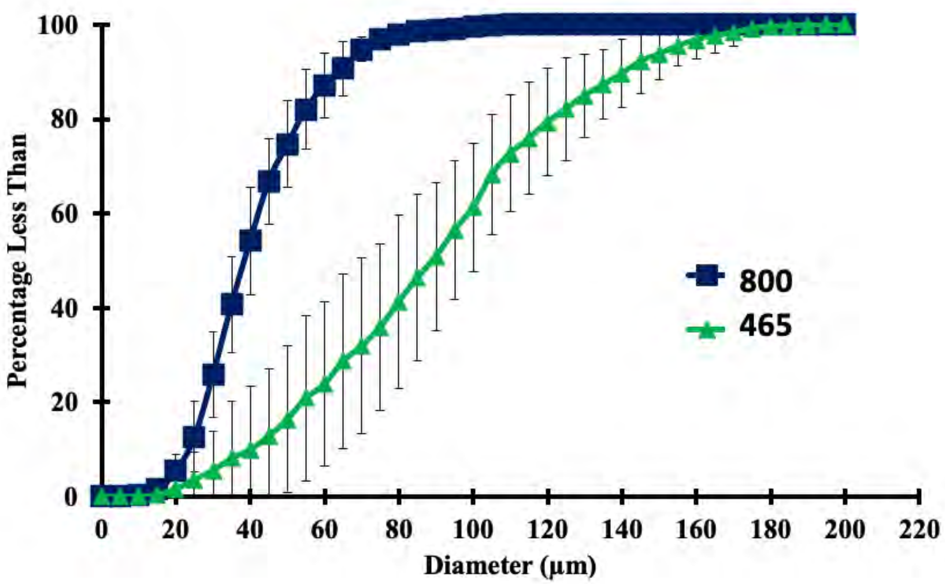
Ice crystal size

- In general, from **a few to over 100 µm** with a mean between **35-45 µm for hardened product**
- A significant impact on the **smoothness** and the **eating quality** of ice cream
- Smaller than about **50 µm for a smooth product**
- The **freezing process is the key** to controlling proper distribution
  - Number
  - Size
  - Shape
- **Increasing total solids** content gives **small ice crystals**
  - Because of the decreasing amount of water in the mix
- **Increasing overrun** can lead to a **decrease in ice crystal size**

Samples	Mean ice crystal size (µm)
540	42.53±3.39[c]
381	54.06±2.29[bc]
900	42.06±5.74[c]
767	49.06±7.50[c]
516	55.60±4.91[c]
849	43.53±2.65[c]
732	51.93±4.59[c]
465	89.53±18.01[a]
670	52.06±2.14[c]
238	43.06±1.19[c]
489	42.03±3.03[c]
800	41.12±4.01[c]
533	45.93±2.71[c]
364	49.63±1.00[c]
510	71.30±6.91[ab]
Min	41.12±4.01
Max	89.53±18.0
Mean of 15 samples	50.90±13.80

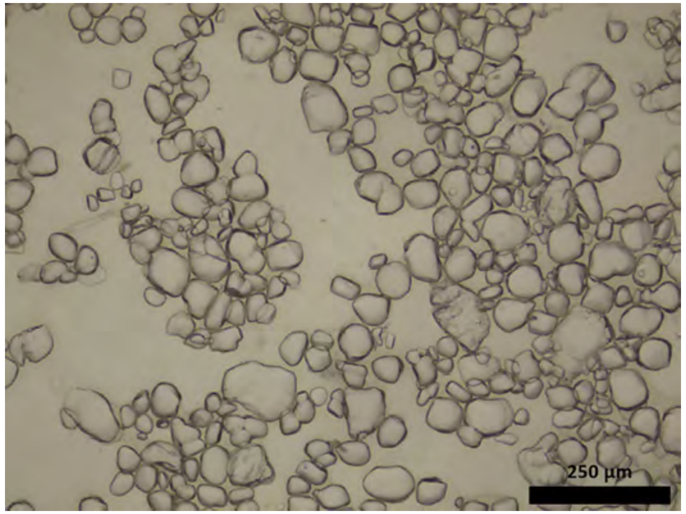
Ice crystal size

- 465 does not **contain any stabilizer or emulsifier** and **has a low total solids content**
- Sweeteners are used to **adjust the freezing point** (465: Honey and 800: Sucrose)
- Spending a **long time in the freezing barrel**-**bigger crystals**
- **Heat transfer rate** between the mix and the refrigerant

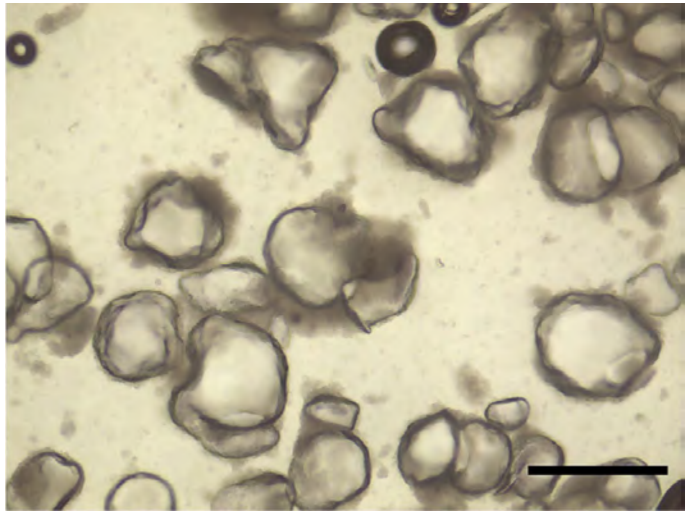


Total solids:
800: 38.75%
465: 32.06%

Sample 800, **mean ice crystal size: 42.12 µm**



Sample 465, **mean ice crystal size: 89.53 µm**



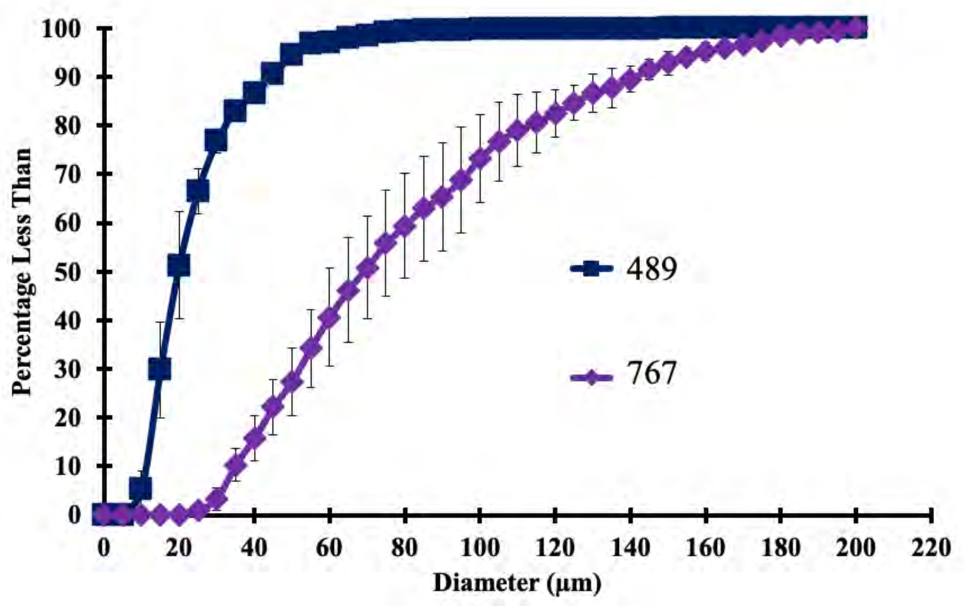
Air cell size

- **Fluffy and scoopable texture**, as well as resistance to melting
- **Controlling air incorporation** is critical for product quality and stability
- Stabilized by **individual fat globules, fat clusters, and proteins**
- Factors:
  - Shear force
  - Dasher speed
  - Overrun

Samples	Mean air cell size (μm)
540	63.37±6.22[b]
381	28.00±1.31[c]
900	28.71±3.12[c]
767	83.18±7.75[a]
516	40.86±3.73[c]
849	75.31±6.96[ab]
732	32.39±7.16[c]
465	77.96±7.77[ab]
670	35.65±4.09[c]
238	32.66±3.55[c]
489	24.01±1.60[c]
800	69.08±15.03[ab]
533	78.86±2.94[ab]
364	34.25±6.50[c]
510	31.29±4.86[c]
Min	24.01±1.60
Max	83.18±7.75
Mean of 15 samples	49.04±22.42

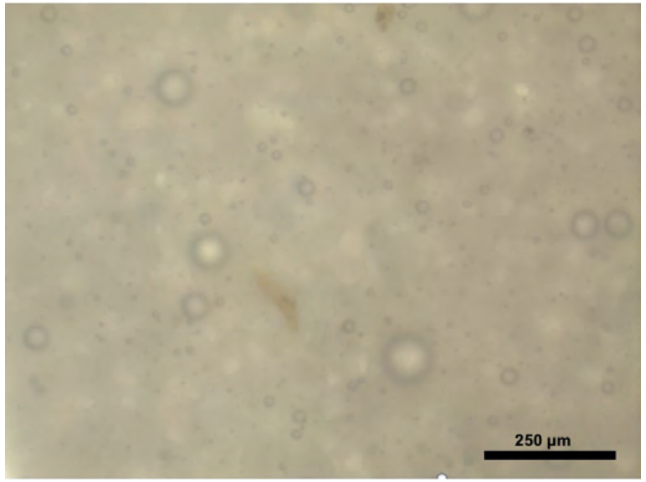
Air cell size

- The **highest mean air cell size: 767,** and **the lowest: 489**
- The **high degree of fat destabilization exhibits smaller air cell size**
- Protein sources are different **(Lupin and pea)**
    - Air holding capacity
- The type of freezers can be different **(batch or continuous)**

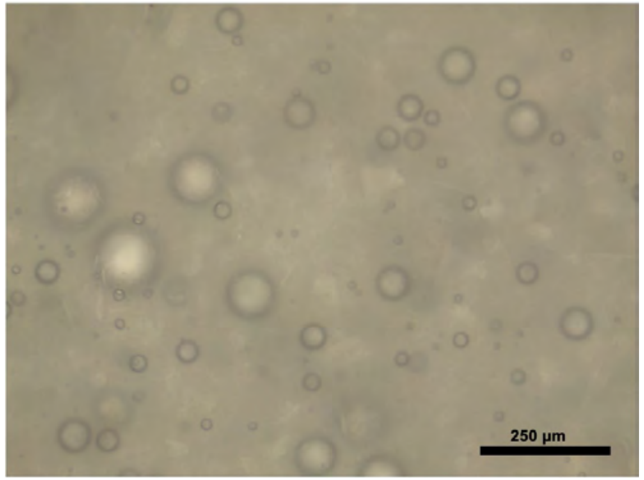


Fat destabilization:
489: 45.72%
767: 3.60%

Sample 489, Mean air cell size: **24.01 µm**



Sample 767, Mean air cell size: **83.18 µm**



Meltdown

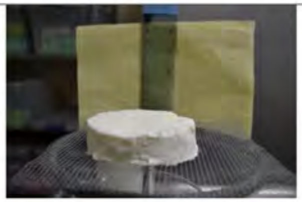
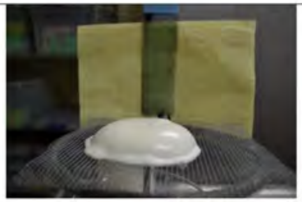
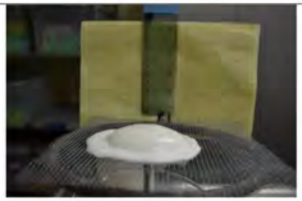
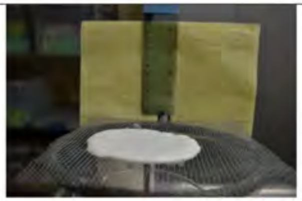
- Microstructure formation
  - By manipulating formulation or changing process parameters
  - is associated with **meltdown behavior**

Contributes to slow meltdown Better shape retention

- Large amount of air and fat clusters
- Viscous serum phase
- Small ice crystals

- **Two types** of meltdown behavior
  - Complete meltdown
  - Foam retention
- **Fat destabilization**, **mix viscosity**, and **overrun** have a major impact

Table 2.1 Example of two types of meltdown behaviors with the same formulation in the ice creams. The complete meltdown sample contains 50% overrun and the foam retention sample has 100% overrun.

Time (min)	Complete meltdown	Foam retention
0		
40		
60		
100		

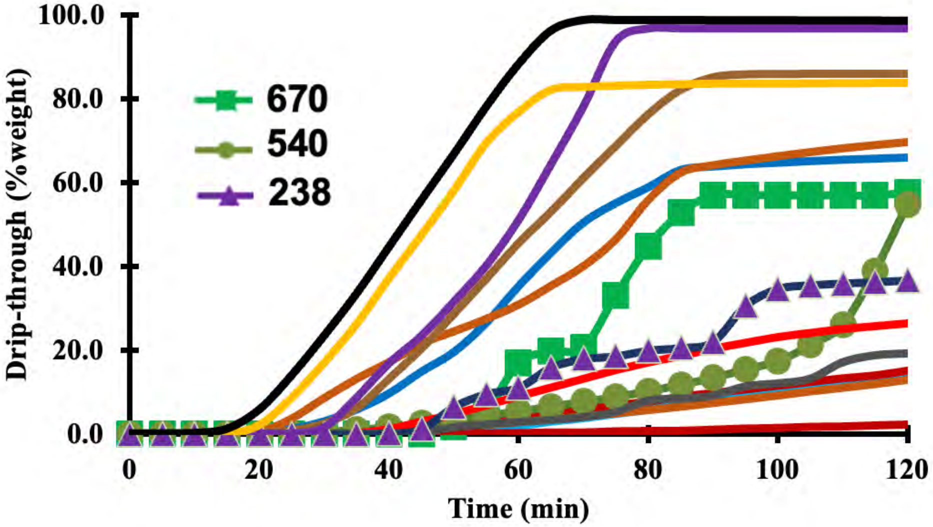
Wu, B. (2023). *Understanding the Meltdown Behavior of Frozen Dessert: From Ice Cream to Model System* (Doctoral dissertation, The University of Wisconsin-Madison).

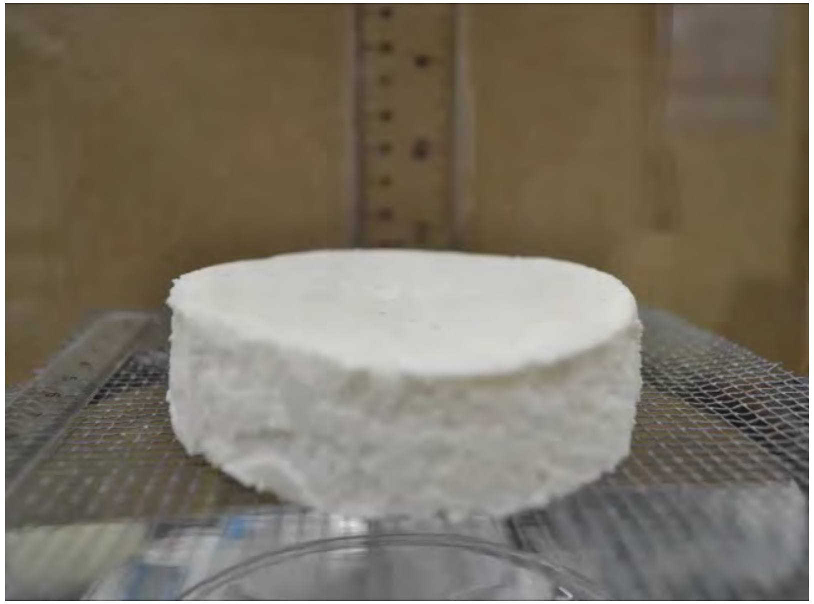
Meltdown

- The **type and structure of protein** make a difference in melting rate and shape retention
- Fat sources
- Fat destabilization, viscosity, and SFC are different
- **Different melting**

670-Oat milk, coconut oil

540-Soy protein, corn oil





238-Pea protein+coconut milk, coconut oil

Pea protein research from the literature

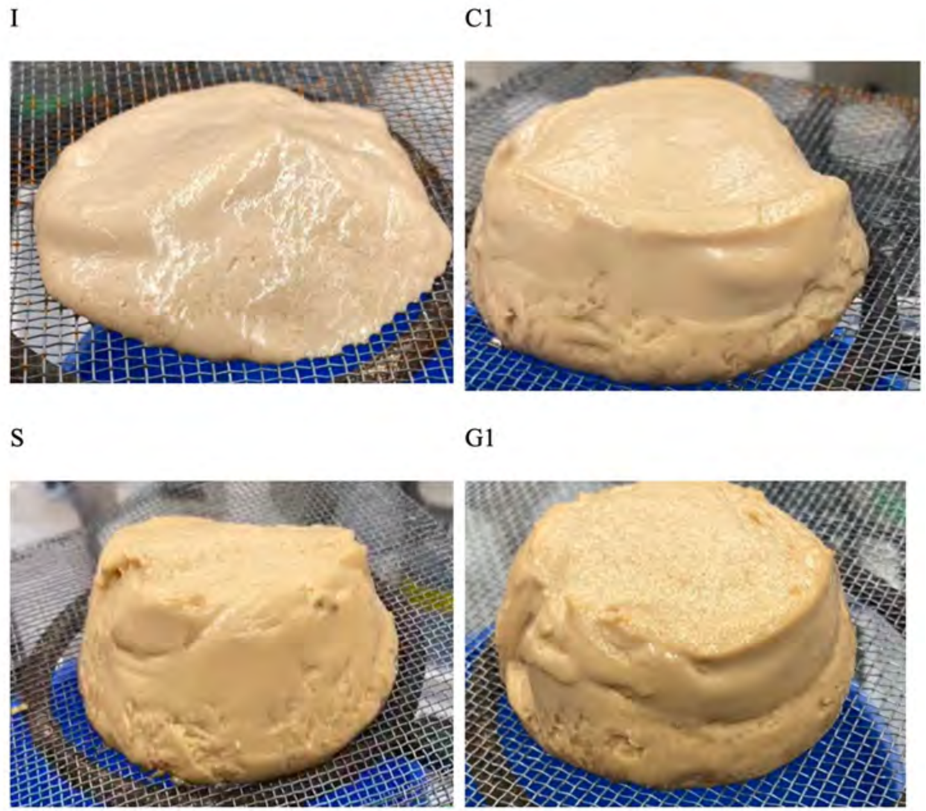


Figure 4-5. Non-dairy frozen dessert after 90 minutes of melting at room temperature. Frozen dessert made with protein I did not retain its shape, while the others did.

- Pea proteins which have **different production methods**
  - Water-based extraction
  - Extraction without chemical solvents
  - Functionalized
  - Highly dispersible
- Different meltdown behavior

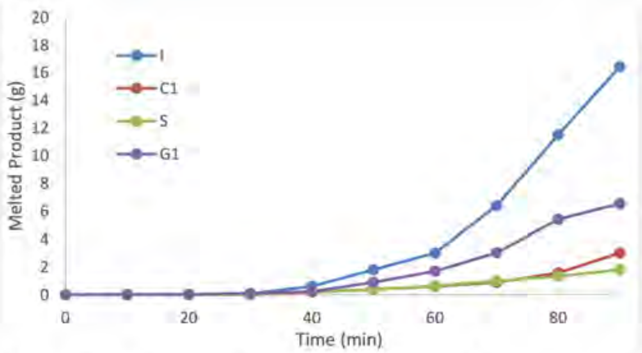
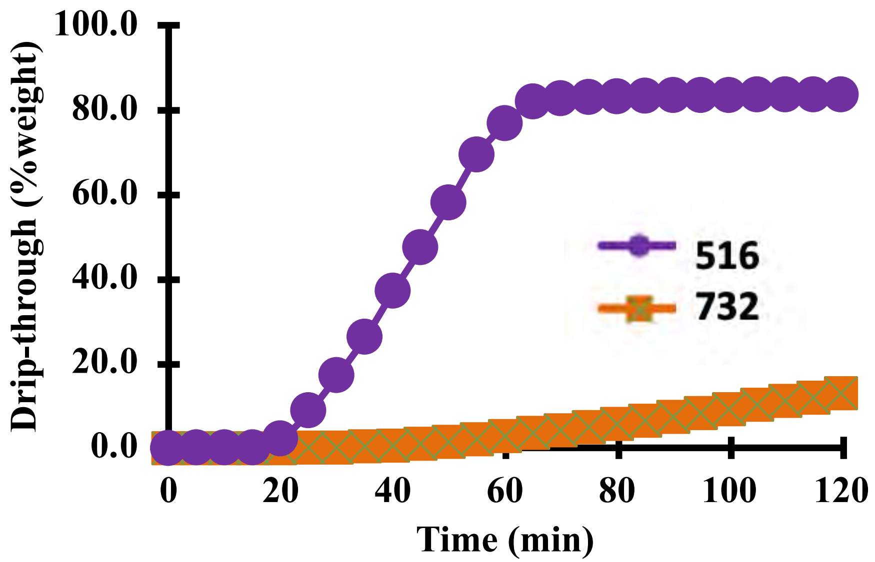


Figure 4-4. Average melting curves across three repetitions. Frozen dessert made with protein I had the highest rate of melting, while frozen dessert made with protein S and C1 had the lowest rates.

Bushek, A. (2020). Assessment of Functional Characteristics of Pea Proteins Important in Frozen Dessert Applications. Penn State University

Meltdown

- Increasing **fat content leads to a slower meltdown rate**, induction time
  - Better shape retention of melted foam
- A **high percentage of fat destabilization provides** rigidity and resistance to drainage
- **Consistency index and yield stress** may indirectly slow the drainage



Sample 516

Sample 732

	Drip Through rate (g/min)	Induction time (min)	Final height of melted ice cream (%)	Fat content (%)	Fat destabilization (%)	Total solids (%)	Consistency index (K, Pa.s^{n})	Yield stress (Pa)
516	1.65±0.36^{a}	15.31±1.15^{f}	8.89±10.18^{hi}	3.80	75.83±4.86^{bc}	35.49±0.57^{ef}	0.11±0.01^{e}	0.13±0.01^{d}
732	0.14±0.01^{d}	30.51±9.75^{de}	75.07±14.96^{ab}	13.00	89.43±0.86^{a}	40.39±0.90^{ab}	0.61±0.20^{bcd}	7.63±2.96^{b}

Conclusion

A wide range of results observed in **compositional and structural** attributes

The **structure** has an influence on the **texture, stability, and acceptability** of the final products by consumers

Critical to understand the **structure of non-dairy frozen desserts** and the role of ingredients

Without an understanding of **various structural phenomena in non-dairy systems**, their structure can not be comprehended

Thanks!

- Prof. Dr. Richard W. Hartel
- Dr. Dieyckson O. Freire
- Payton Gladem
- Hartel Lab

Questions?

- Contact: Dr. Didem Sözeri Atik, sozeriatik@wisc.edu ; didem.sozeri@yahoo.com