DISCLOSURE STATEMENT

- Consult for several plant-based food companies
- Scientific advisor for several plant-based food companies (with stock options)

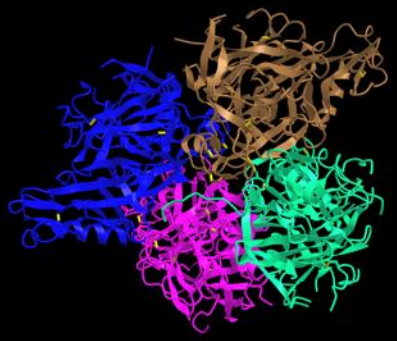
PLANT-BASED FOODS:
DESIGN, PRODUCTION, AND PROPERTIES

DAVID JULIAN MCCLEMENTS

BIOPOLYMERS AND COLLOIDS LABORATORY

DEPARTMENT OF FOOD SCIENCE

UNIVERSITY OF MASSACHUSETTS



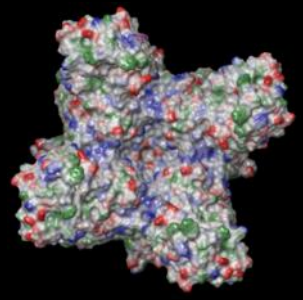
THE RISE OF PLANT PROTEIN FOODS:
MEAT, SEAFOOD, EGG, AND DAIRY

$7 billion sales in 2020 (up 27%)

(Good Food Institute, USA)

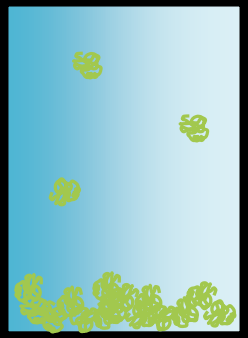
PLANT PROTEIN INGREDIENTS

REPLACING SYNTHETIC AND ANIMAL INGREDIENTS

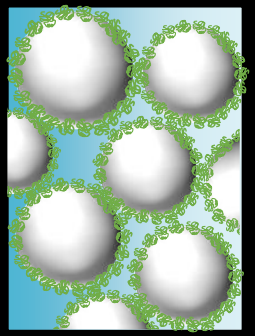


Plant Protein Ingredients

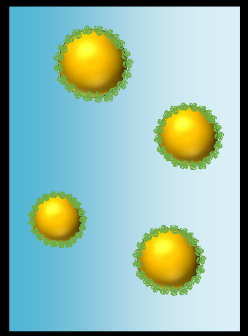
Foods



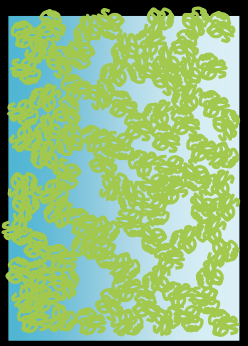
Solubility



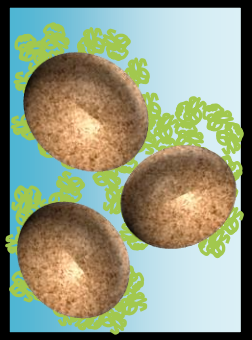
Foaming



Emulsification



Gelation



Binding

PLANT PROTEIN INGREDIENTS
SOURCES


Soybeans


Peas


Corn


Mung bean

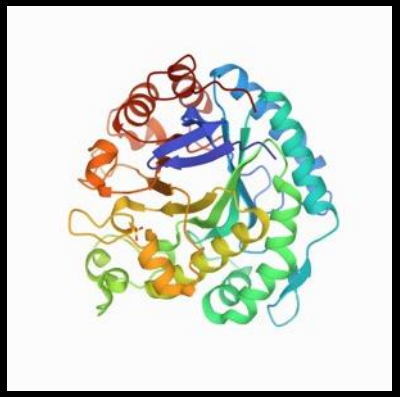

Duckweed

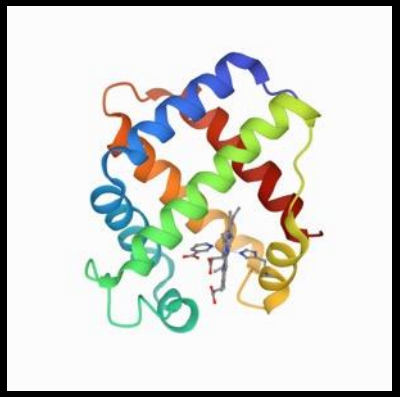
Desirable Attributes

- Abundant
- Economic
- Sustainable
- Reliable
- Extractable
- Functional

PLANT PROTEIN INGREDIENTS

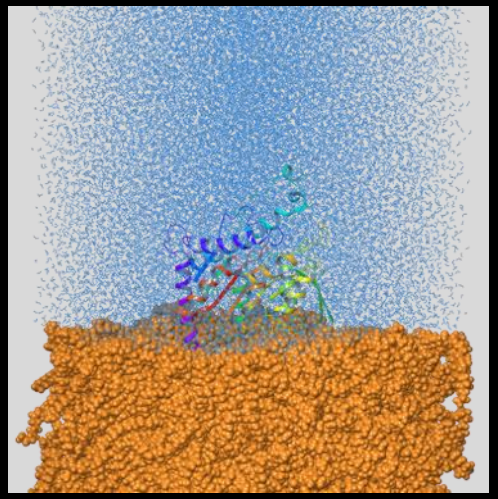
MOLECULAR PROPERTIES DETERMINE FUNCTIONAL PERFORMANCE





Molecular Properties

- Dimensions
- Flexibility
- Stability
- Surface charge
- Surface hydrophobicity
- Chemical reactivity



PLANT PROTEIN INGREDIENTS

Isolation and Purification

Soybeans

Oil bodies

Starch Granules

Protein bodies

Cotyledon Cells

Protein Bodies

Protein aggregates

Protein subunits

β-conglycinin

Glycinin

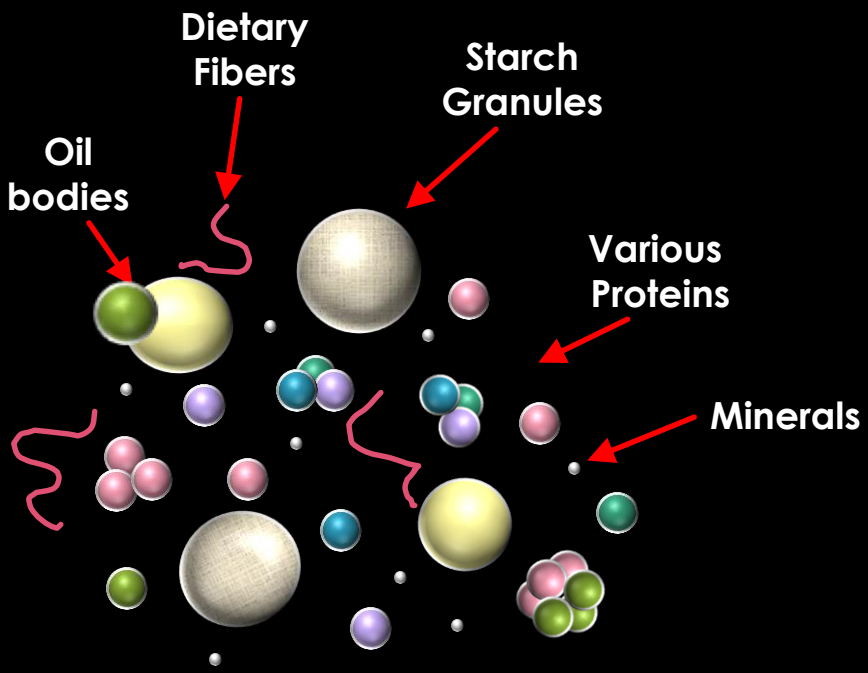
Diverse protein molecules

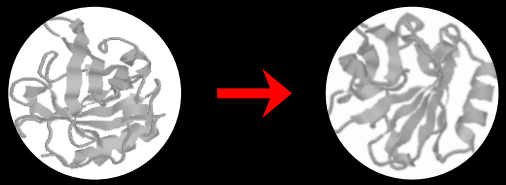
PLANT-PROTEIN INGREDIENTS

Functional Reliability

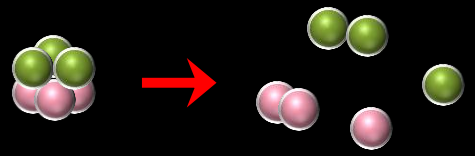
Plant Protein Ingredient

Complex Mixture of Protein and Non-Protein Substances





Protein Conformation



Protein Aggregation State

PLANT-PROTEIN INGREDIENTS

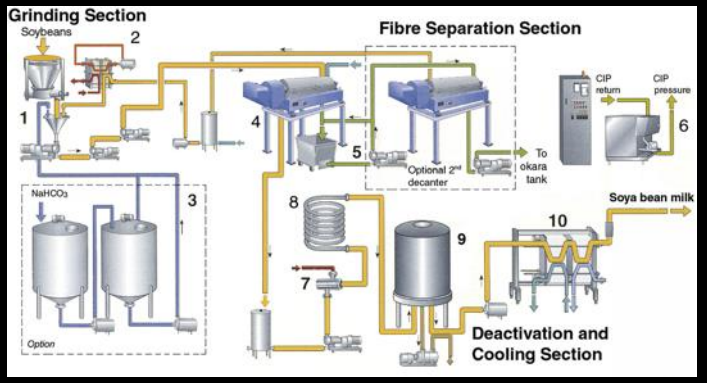
CHALLENGES & RESEARCH NEEDS

CHALLENGES

- Availability of plant-derived ingredients that are abundant, sustainable, reliable, and functional

RESEARCH NEEDS

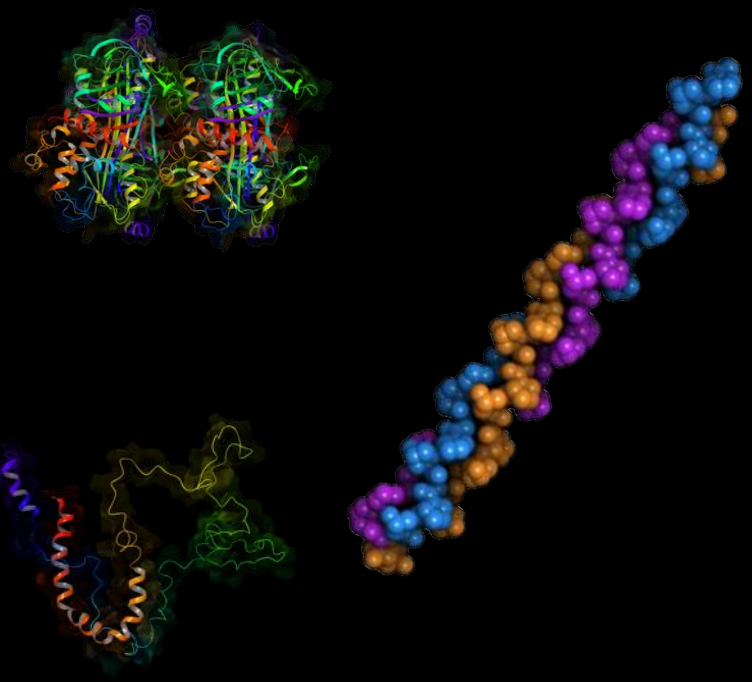
- Crop breeding
- Precision agriculture
- Extraction & purification



Sustainable

Preece et al (2019). Innovative Food Science & Emerging Technologies. 43, 163-172

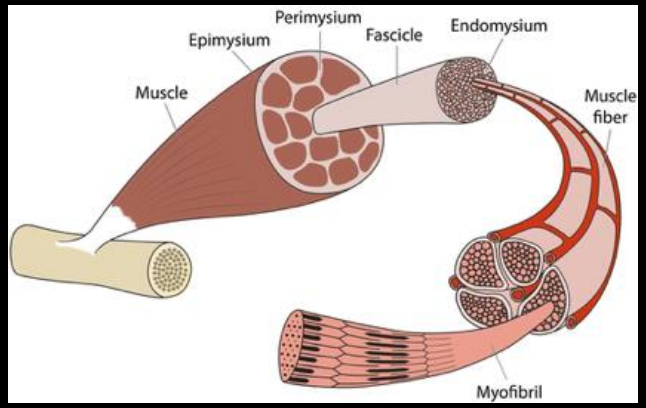
FORMULATING PLANT-BASED FOODS
STRUCTURAL DESIGN PRINCIPLES



Animal Proteins have Unique Structures & Functionalities

MEAT & SEAFOOD

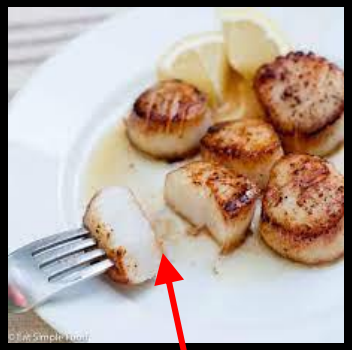
STRUCTURALLY COMPLEX MATERIALS

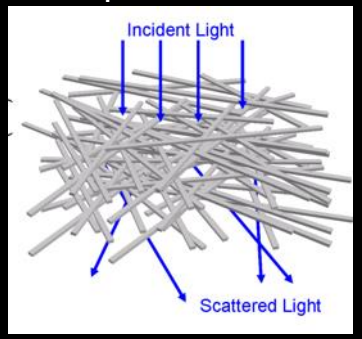


MIMICKING REAL MUSCLE FOODS:
MULTISENSORIAL ENGINEERING

Sound
Bubbling & Evaporation

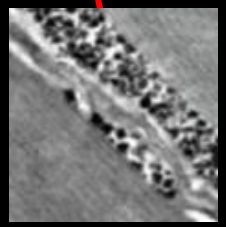
Appearance
Light Absorption & Scattering

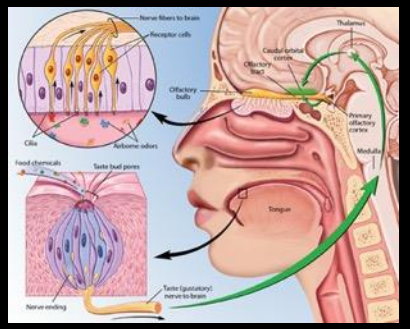




Texture
Small & Large Deformation

Aroma
Specific Volatile Profile





Mouthfeel
Breakdown/Texture-Time

Microstructure
Organization

Taste
Specific Tastant Profile

What is the structural basis of deliciousness?

CONSTRUCTING PLANT-BASED FOODS

PROCESSING METHODS

Extruders

Shear Cells

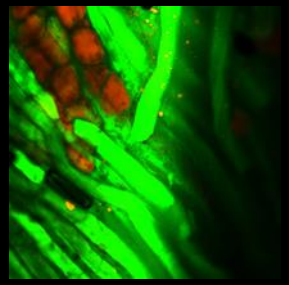
Mixers

3-D Printers

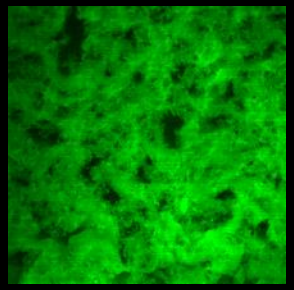
CONSTRUCTING PLANT-BASED FOODS
SOFT MATTER PHYSICS APPROACHES

Muscle &
Connective Tissue

Adipose
Tissue

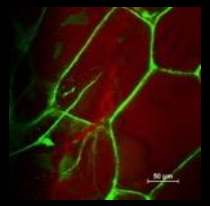


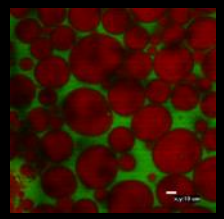
Animal-based



Plant-based

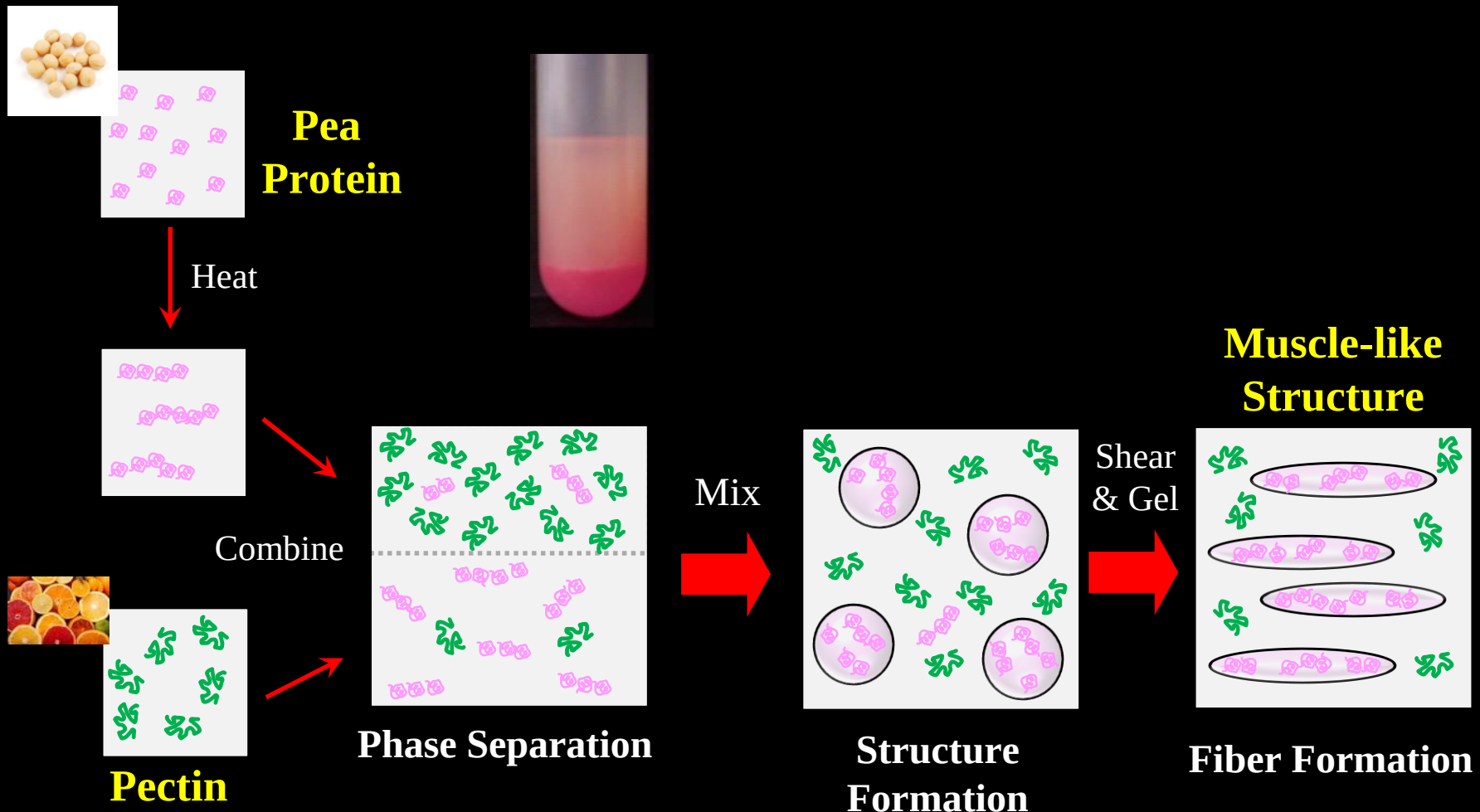
Animal-based





Plant-based

Constructing Plant-Based Foods
Soft Matter Physics Methods



PLANT-BASED SCALLOP

EGGS:
COMPLEX COLLOIDAL DISPERSIONS

> $27 million (2020)
(Good Food Institute, USA)

HEN'S EGGS:
FAMILIAR & VERSATILE

QUALITY

APPEARANCE, TEXTURE, MOUTHFEEL & TASTE

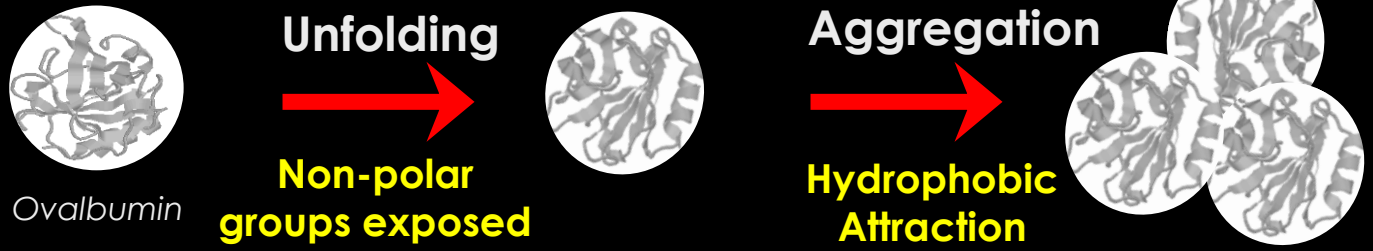
NUTRITION

PROTEINS (12%), LIPIDS (10%), VITAMINS A, D, E, CHOLINE, IRON, AND FOLATE

VERSATILITY

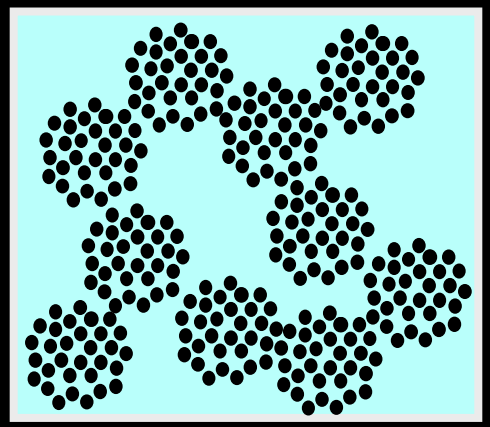
MAYONNAISE, SALAD DRESSING, MERINGUE, DESSERTS, CAKES….

PROTEIN FUNCTIONALITY:
THERMAL GELATION



Ovalbumin

Heat-set
Irreversible
Opaque Gel

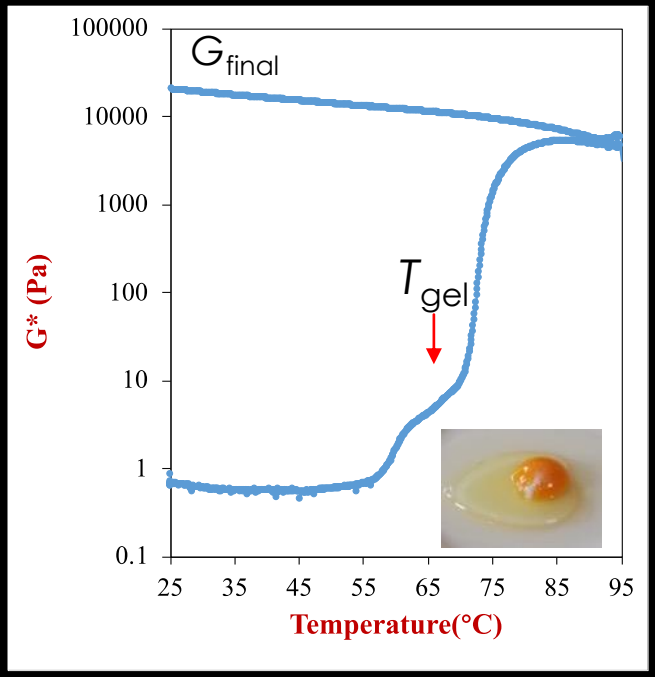


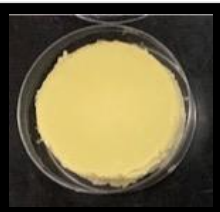
Physical Properties

Appearance, texture, cookability, mouthfeel

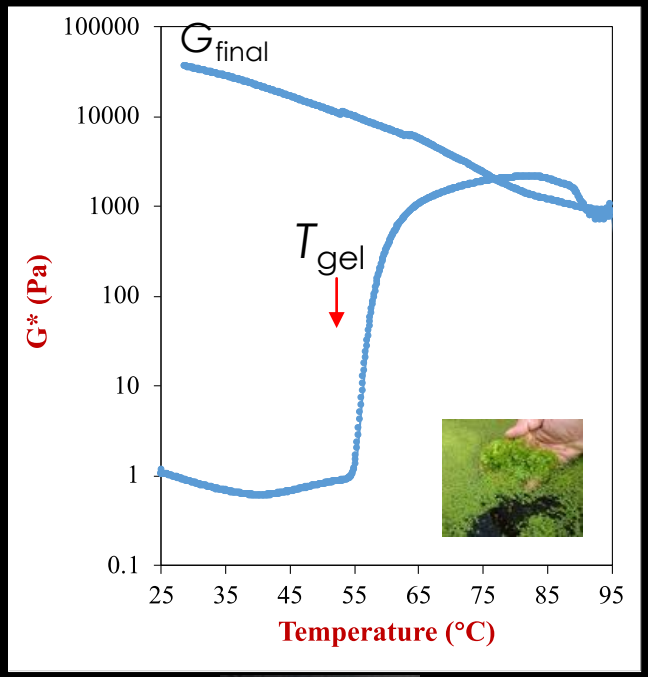
MIMICKING REAL EGG:
PHYSICOCHEMICAL CHARACTERIZATION

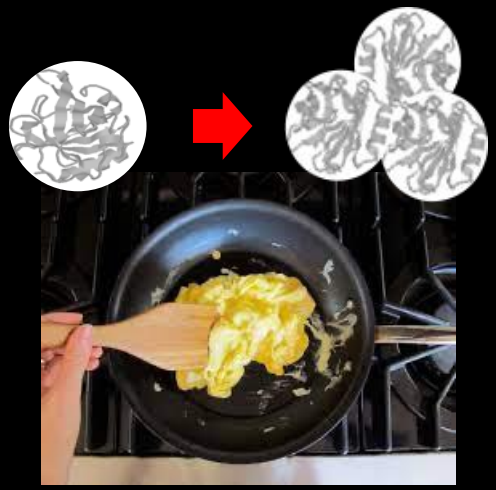
Egg White





Rubisco

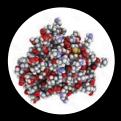




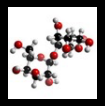
Zhou, Vu, McClements (2022). Formulation and characterization of plant-based egg white analogs using RuBisCO protein. Food Chem. 397:133808

MILK & DAIRY PRODUCTS

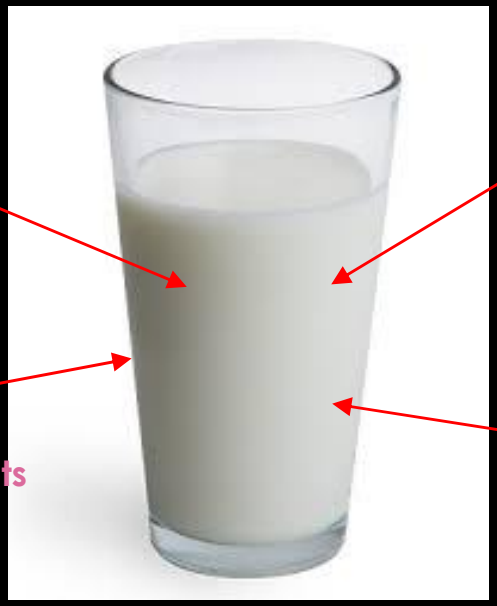
COMPLEX COLLOIDAL DISPERSIONS

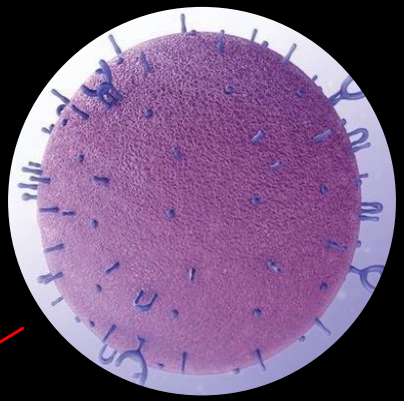


Whey proteins
(2-3 nm)



Sugars and salts
(1-2 nm)





Milk Fat Globules
(1000-5000 nm)

Casein Micelles
(20-200 nm)

QUALITY ATTRIBUTES

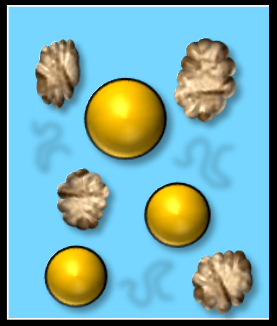
NUTRITIONAL PROFILE

VERSATILITY

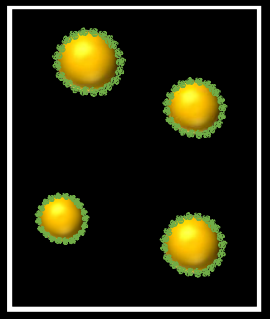
PLANT-BASED MILKS:

FABRICATION METHODS

Top-Down

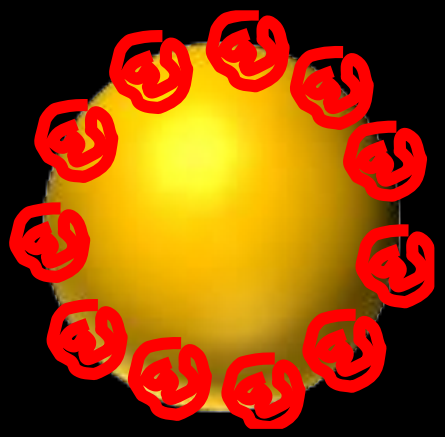


Bottom-Up



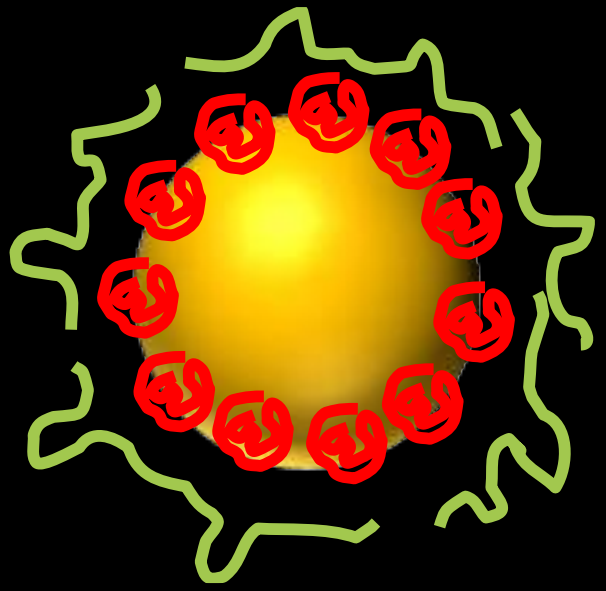
STABILIZATION BY MULTILAYER TECHNOLOGY
IMPROVE PH AND HEAT STABILITY

CONVENTIONAL



Highly susceptible
to changes in pH
and temperature

FIBER - COATED



Resistant to
changes in pH
and temperature

FORMULATING PLANT-BASED FOODS

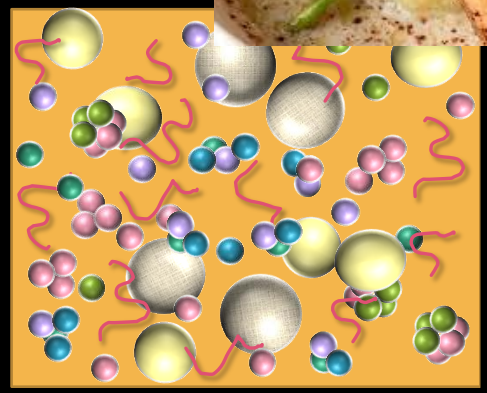
CHALLENGES & RESEARCH NEEDS

CHALLENGE

- To create plant-based products that accurately simulate animal-based ones

RESEARCH NEEDS

- Innovative processing technologies
- Advanced analytical instrumentation
- Soft matter physics theories
- Computer simulations



Sustainable

NEXT-GENERATION PLANT-BASED FOODS: DESIGNING FOR HEALTH

Ingredients

Water, Coconut Oil, Modified Potato Starch, Gluten Free **Oat** Fibre, Maize Starch, Salt, Modified Maize Starch, Calcium, Thickeners (Carrageenan, Guar Gum), Natural Flavourings, Acidity Regulators (Lactic Acid, Sodium Lactate), Colour (Carotenes).

Nutrition information	**Per 100g**
Energy	1297kJ/313kcal
Fat	25.9g
of which Saturates	21.6g
Carbohydrate	18.3g
of which sugars	0.1g
Protein	0.1g
Salt	1.6g
Calcium	150mg (19% RI)

NEXT-GENERATION PLANT-BASED FOODS: DESIGNING FOR HEALTH

Nutrition Facts

Serving Size: 1 slices (85g)

Amount Per Serving	
Calories 170	Calories from Fat 41
	% Daily Value*
Total Fat 4.5g	**7%**
Saturated Fat 1g	**5%**
Trans Fat 0g	
Cholesterol 0mg	**0%**
Sodium 610mg	**25%**
Total Carbohydrates 32g	**11%**
Dietary Fiber 9g	**36%**
Sugars 0g	
Protein 0.5g	
Vitamin A	0%
Vitamin C	0%
Calcium	2%
Iron	0%

* Percent Daily Values are based on a 2000 calorie diet.

INGREDIENTS: WATER, OLIVE OIL, KONJAC POWDER, PEA STARCH, POTATO STARCH, PEA PROTEIN, SEA SALT, ORGANIC AGAVE NECTAR, SEAWEED POWDER, FENUGREEK, ALGINATE(FROM SEAWEED), PAPRIKA, CALCIUM HYDROXIDE.

NEXT-GENERATION PLANT-BASED FOODS:
DESIGNING FOR HEALTH

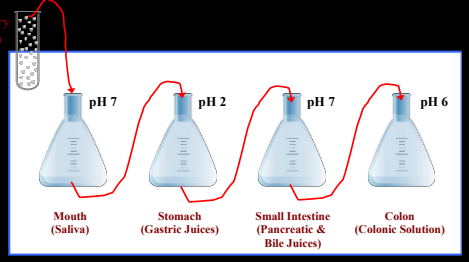
NUTRITIONAL DESIGN & FORTIFICATON

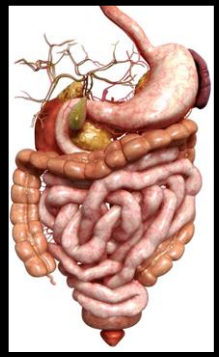
- MACRONUTRIENT COMPOSITION
- MICRONUTRIENT COMPOSITION
- NUTRACEUTICALS AND DIETARY FIBERS

GASTROINTESTINAL FATE

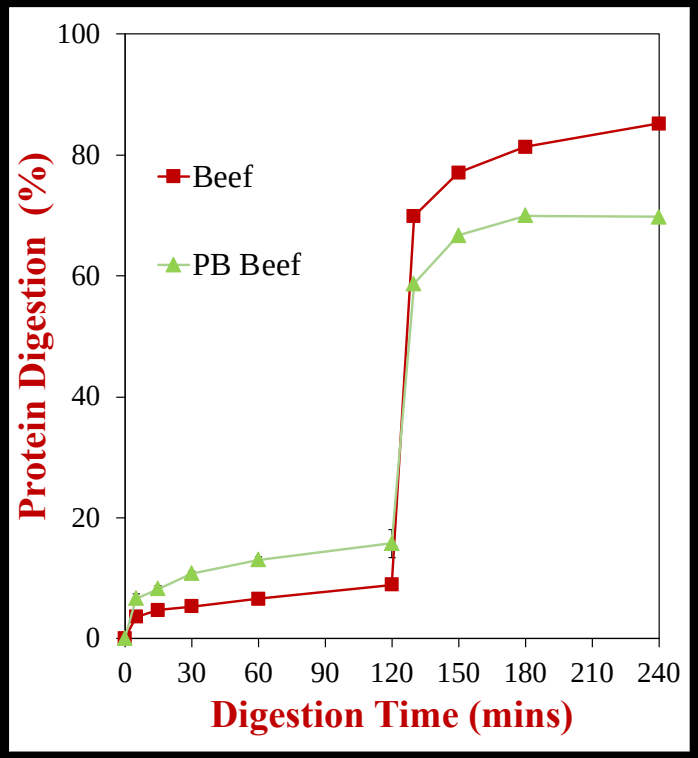
- DIGESTIBILITY
- BIOAVAILABILITY
- MICROBIOME EFFECTS

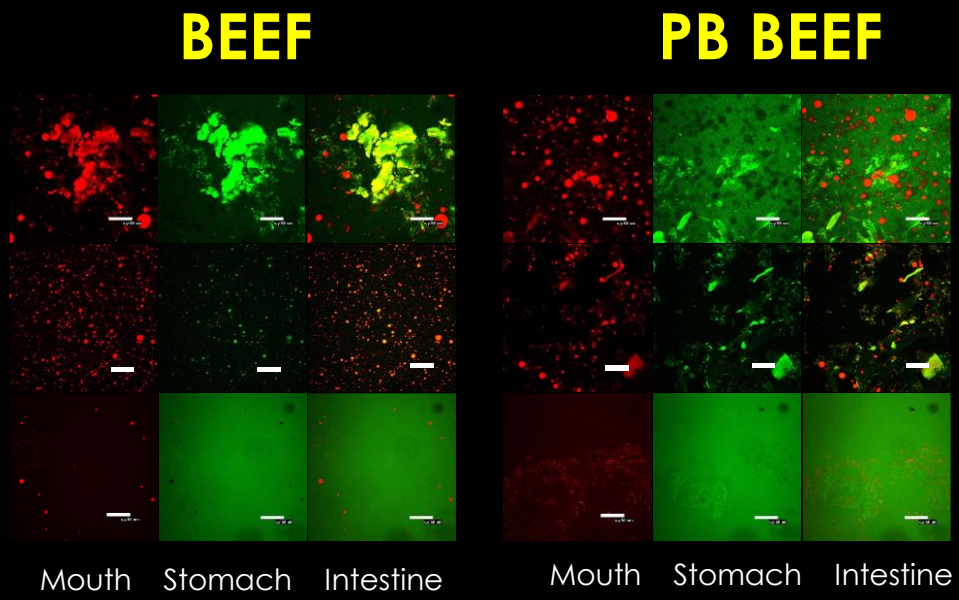
GASTROINTESTINAL FATE





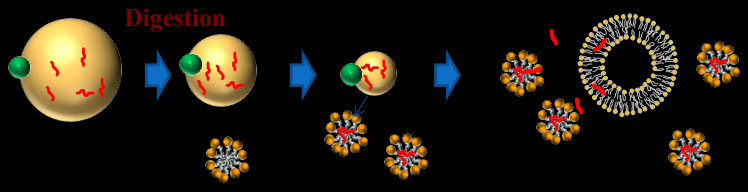
Digestibility
Bioavailability

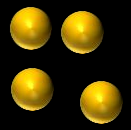


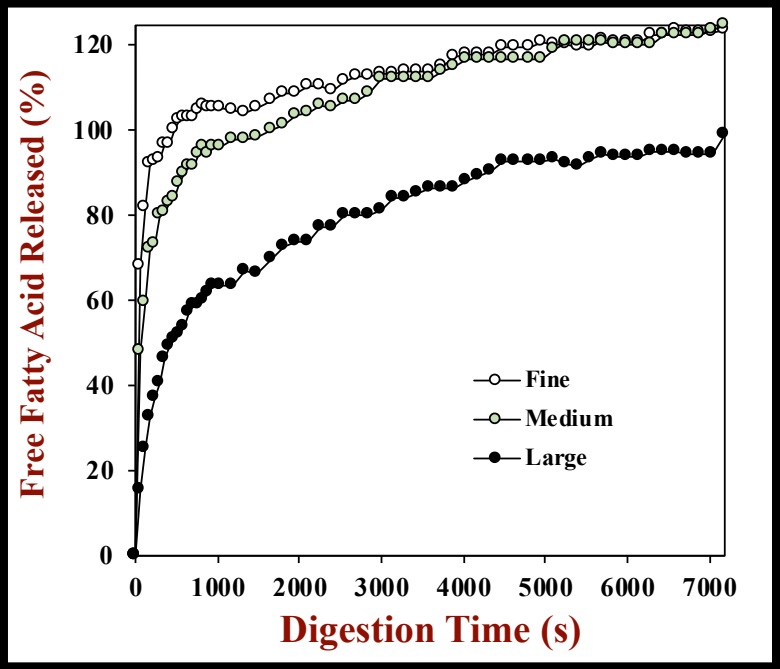


Zhou et al (2021). Digestibility and Gastrointestinal Fate of Meat versus Plant-Based Meat Analogs: An in Vitro Comparison
Food Chemistry 364(2):130439

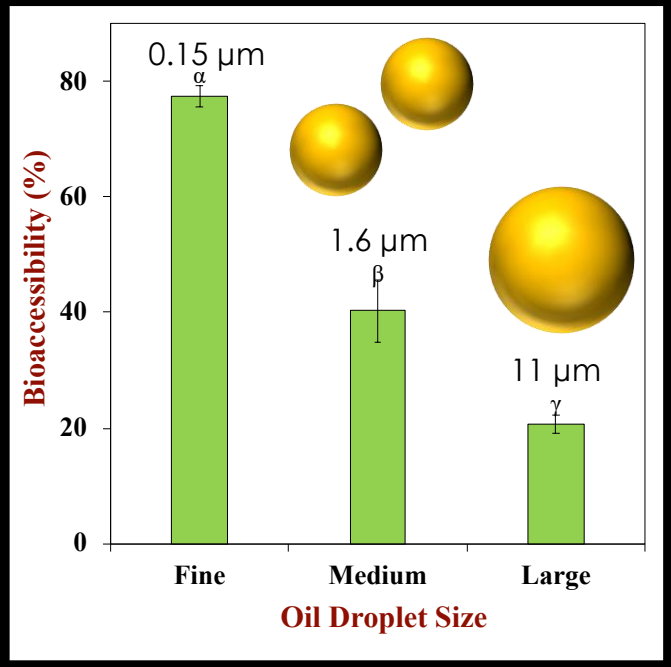
PLANT-BASED MILK FORTIFICATION





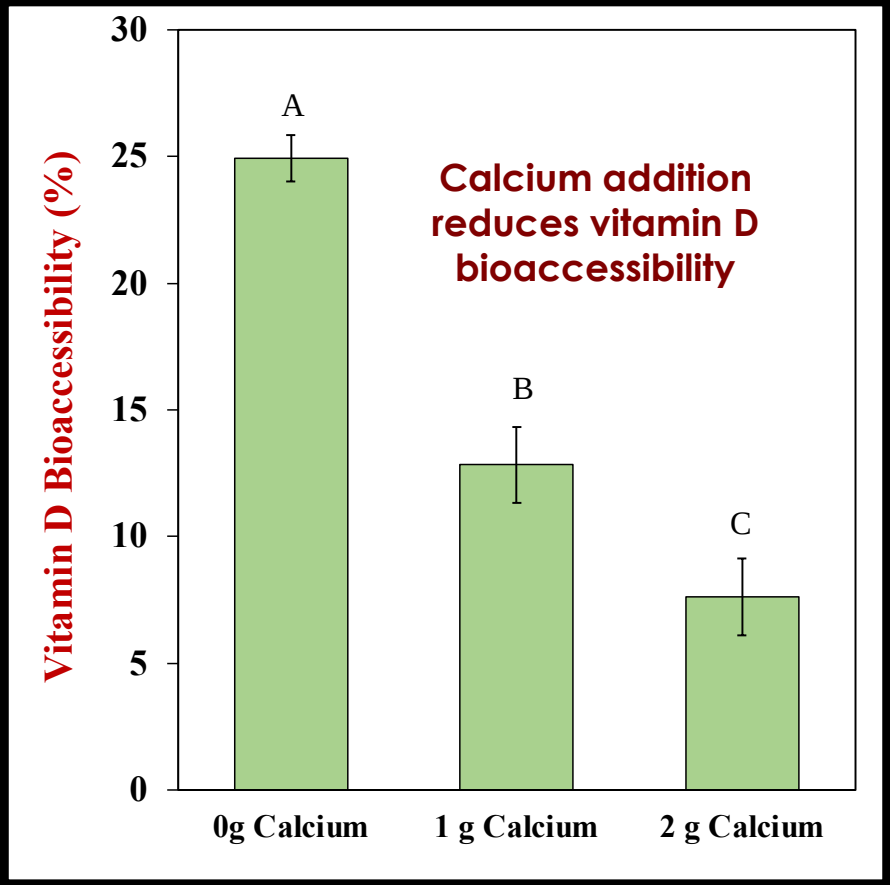


Vitamin E-loaded plant-based emulsions

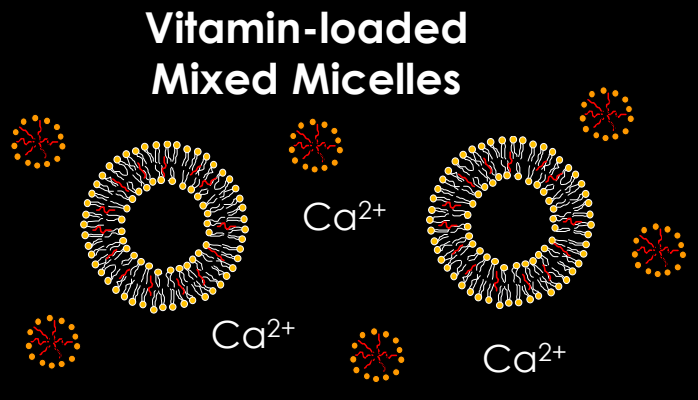


Tan et al. (2021). Bioaccessibility of oil-soluble vitamins (A, D, E) in plant-based emulsions: Impact of oil droplet size *Food & Function* 12(9)

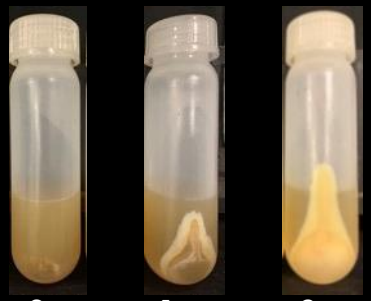
PLANT-BASED MILK FORTIFICATION



Vitamin D-fortified Almond Milk



Calcium Soap



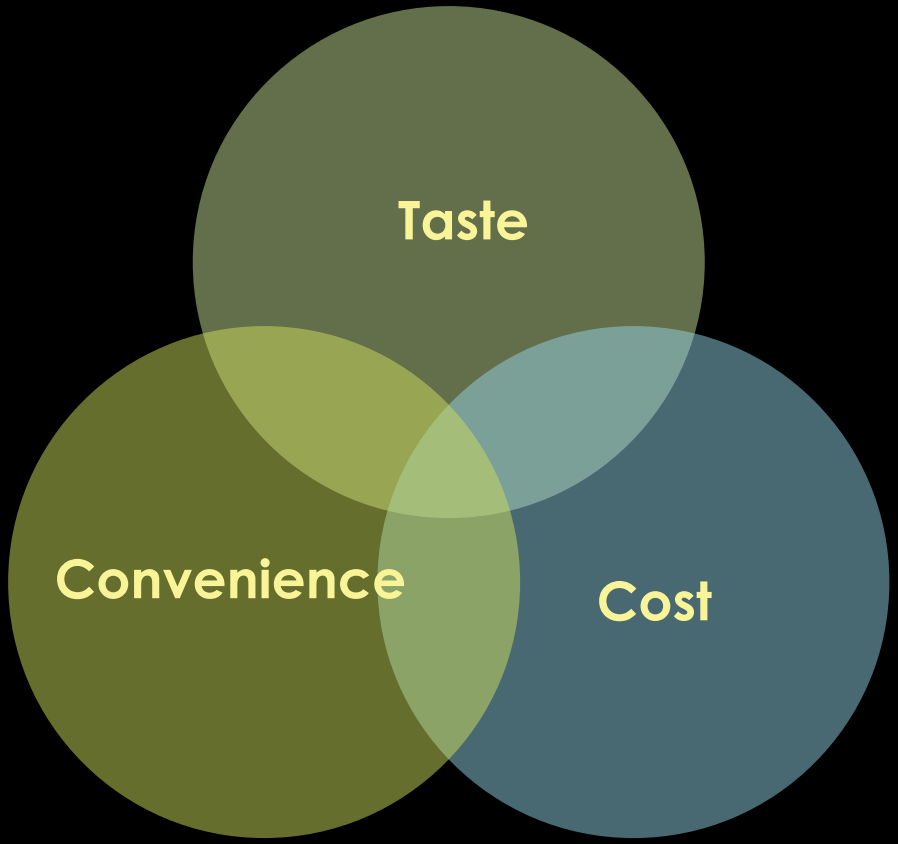
Tan et al. (2019). Impact of calcium levels on lipid digestion and nutraceutical bioaccessibility in nanoemulsion delivery systems studied using standardized INFOGEST digestion protocol, *Food & Function* 11(1)

DESIGNING FOR HEALTH
CHALLENGES & RESEARCH NEEDS

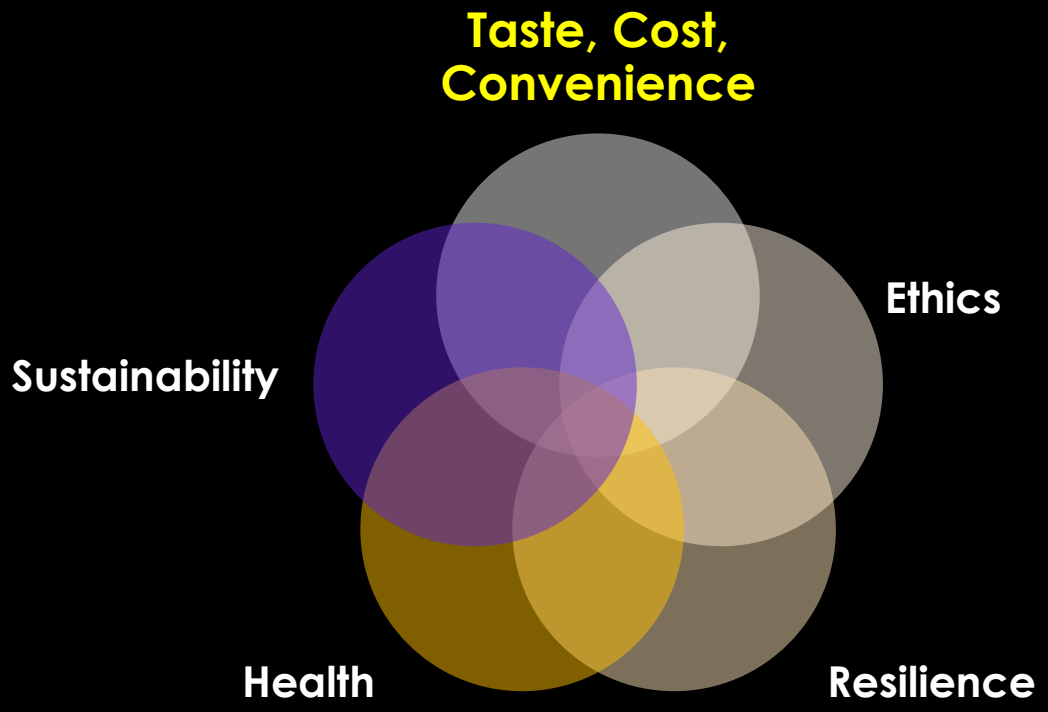
CHALLENGES
- Creating plant-based foods with nutritional profiles that match or exceed animal-based ones

RESEARCH NEEDS
- Formulating for health & nutrition
- In vitro digestion models
- In vivo human feeding studies

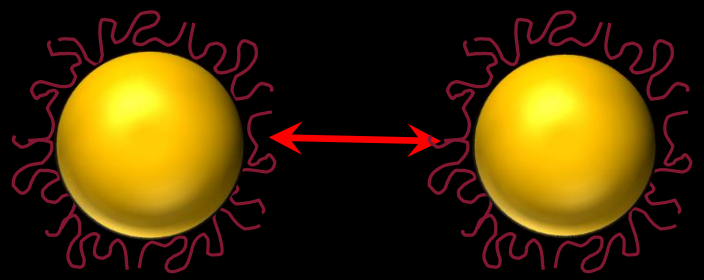
FOOD SCIENCE & ENGINEERING:
THE OLD PARADIGM



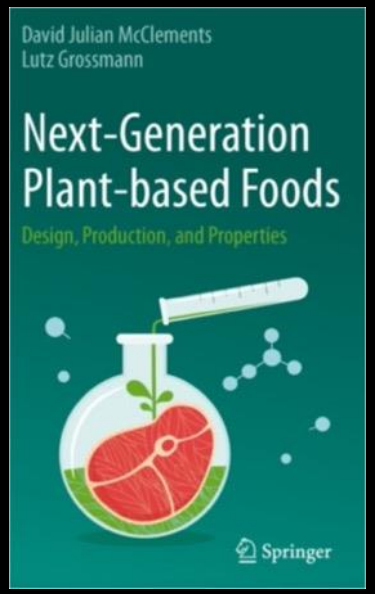
FOOD SCIENCE & ENGINEERING:
THE NEW PARADIGM



THE FUTURE



- Market for plant-based foods expanding due to ethical, environmental, and health reasons
- Many successful products on market already.
- Market expansion depends on better design of sensory, nutritional, & functional attributes
- Need better understanding of structure-function relations
- Need more consistent functional ingredients



ACKNOWLEDGEMENTS

NSF

UMASS AMHERST

NASA

USDA

THE GOOD FOOD INSTITUTE

FUTURE DIRECTIONS

INGREDIENTS AND PROCESSING

- IDENTIFICATION, ISOLATION & CHARACTERIZATION
- INGREDIENT FUNCTIONALLY & COMPLEX MATERIALS

SENSORY

- APPEARANCE, TEXTURE, TASTE

NUTRITION

- NUTRITIONAL PROFILE
- DIGESTIBILITY

SUSTAINABILITY

- ENVIRONMENTAL IMPACT

SOCIOECONOMICS

- COST AND SCALABILITY
- SOCIAL IMPACT