Food Structures: processing, digestibility and nutrient bioavailability

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Food structures and assemblies

> All foods come from living organisms (plants and animals) where various components interact to produce biological systems

> These interactions and the constituent matrix become relevant when these organisms are consumed as food

> Nutrients are contained in these biological systems - human digestive processes

> Fibrous structures (e.g. muscle); Fleshy materials (e.g. fruits, tubers, vegetables); Encapsulated embryos (e.g. grains and pulses); Complex fluids (e.g. milk)
### Structure anatomy of plant foods

<table>
<thead>
<tr>
<th>Classification</th>
<th>Fleshy structures</th>
<th>Encapsulated embryos</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Hierarchical composites of hydrated cells that are bound together at cell walls and middle lamella, and exhibit turgor pressure</td>
<td>Dispersion of starch, protein, lipids assembled into discrete pockets</td>
</tr>
<tr>
<td>Microstructure</td>
<td><img src="image1.png" alt="Image of tuber microstructure" /> <img src="image2.png" alt="Image of fruit microstructure" /> <img src="image3.png" alt="Image of vegetable microstructure" /></td>
<td><img src="image4.png" alt="Image of cereal microstructure" /> <img src="image5.png" alt="Image of legume microstructure" /> <img src="image6.png" alt="Image of tree nut microstructure" /></td>
</tr>
<tr>
<td>Examples of plant foods</td>
<td>Tubers</td>
<td>Fruits</td>
</tr>
</tbody>
</table>

The table above categorizes plant foods into two groups: fleshy structures and encapsulated embryos. Fleshy structures include hierarchical composites of hydrated cells, bound together at cell walls and middle lamella, and exhibiting turgor pressure. Encapsulated embryos, on the other hand, involve the dispersion of starch, protein, and lipids assembled into discrete pockets. The images depict the microstructure of tubers, fruits, vegetables, cereals, legumes, and tree nuts.
Hierarchical assemblies of foods in nature

- **1 Å**
  - Water ~ 3 Å
- **1 nm**
  - Glucose molecules ~ 1.5 nm
- **10 nm**
  - Cellulose microfibrils ~ 3-4 nm
- **100 nm**
  - Primary cell walls ~ 100 nm thickness
- **1 µm**
  - Lipid bodies ~ 0.5-2.5 µm
  - Protein bodies ~ 0.1-25 µm
- **10 µm**
  - Starch granules ~ 1-100 µm
  - Parenchyma cells ~ 10-200 µm
- **100 µm**
  - Tissues ~ 100 µm to few mm
- **1 mm**
  - Plant organs order of 1 mm

- **Molecules**
- **Polymers**
- **Cell wall**
- **Organelle**
- **Cell**
- **Tissue**
- **Organ**
Food structure and processing

Plant food organ

Particle size reduction

Wheat flour

Mechanical processing (milling)

Mechanical processing (grinding)

Thermal cooking and mashing

Starch gelatinisation in cooked potatoes

Bean paste

Cell separation

Cell rupture

Ground almond meal

Disruption of cell walls, release of nutrients

Starch gelatinisation, protein denaturation, separation of cells

Tissues

Particles

Ground almond meal
Food structure and digestion

Disassembly of food structure during mastication

Ingested food (raw or processed)

Particles

Particle size reduction, lubrication (bolus)

Oral mastication

Tissues

Disruption of cell walls, release of nutrients, partial starch degradation, lipid flocculation

Cells of cooked legumes and tubers

Separation of cells, encapsulated nutrients

Cells of hard raw nuts, fruits and vegetables

cells of hard raw nuts, fruits and vegetables
Food structure and digestion

Disassembly of food structure during gastric-intestinal digestion

- Digestion in stomach and small intestine
  - Erosion of food particles
  - Enzymatic hydrolysis of starch and protein
  - Lipid emulsification and digestion

- Nutrient released
- Enzyme degradation

- Particles
- Tissues
- Cell separation
- Cell rupture

- Nutrient encapsulated
  - Enzyme diffusion

- CO₂, H₂, CH₄, SFCA

- Fermentation in large intestine by bacteria and faecal excretion

- Anus
Food Matrix/Structure and Nutrient Delivery

- Changes in food matrix/structures during processing and digestion influence the release of nutrients in the GIT

- Bioavailability of nutrients:
  - availability in the intestinal lumen
  - absorption and/or retention in the body
  - utilization by the body

- Food matrix will the availability of nutrient (the kinetics of release and absorption of nutrients) - influence physiological process – human health

- Designing food structures/matrices to develop new types of healthy foods
Lipids in Foods

> Lipids in natural foods occur in many different forms; in many cases - triglycerides are coated with a stabilising layer or multilayer of membrane phospholipids
> Lipids in processed foods – in the form of oil-in-water or water-in-oil emulsions
> Emulsions are stabilised by proteins, phospholipids, monoglycerides and/or diglycerides
> Surrounding structures (cells, seed oil bodies etc) have important influence on lipid digestion and bioavailability
Natural Food Emulsions: Milk

> The diameter of the fat globules: 0.1-10 μm.
> Milk fat globule membrane (MFGM): proteins, phospholipids
Lipids in Natural Foods: Plant Seed/Nut Oil Bodies

- Lipids stored in oil bodies or “oleosomes”
- Oil droplet surrounded by a monolayer of phospholipids embedding proteins.

Food Emulsions

Surrounding structures have important effect on food properties
Factors that Influence Lipid Digestion in Emulsified Systems

- Droplet size and state of flocculation in the GIT
- Nature of the interfacial layers
- Physical state of lipids; solid/liquid fat content
- Food matrix effects, e.g. fibres
TAG levels after test meals containing 50 g test fat from whole almond seed macroparticles (∆), almond oil and flour (○), or sunflower oil (control, ▪).

Impact of Emulsion Structure on Lipid Digestion

(From Golding et al, 2010)
Emulsion gels

**Whey protein oil-in-water emulsion**
(10 wt% protein, 20 wt% soya oil, $d_{4,3}: 0.45 \, \mu m$)

Add NaCl

**Emulsions** containing 10, 25, 100 and 200 mM NaCl

Heated in 90 °C for 30 min
Cooled to 4°C

Gels with different structures

Green represents protein
Red represents oil
Black represents water or air
## Characterization of emulsion gel

<table>
<thead>
<tr>
<th>Gel type</th>
<th>Gel strength (kPa)</th>
<th>Hardness before fracture (N)</th>
<th>Fracture force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 mM NaCl</td>
<td>7.3±1.8*</td>
<td>19.2±0.6*</td>
<td>3.9±0.3*</td>
</tr>
<tr>
<td>25 mM NaCl</td>
<td>23.0±1.8**</td>
<td>56.5±1.3**</td>
<td>7.0±0.1**</td>
</tr>
<tr>
<td>100 mM NaCl</td>
<td>107.0±5.2****</td>
<td>77.8±0.4****</td>
<td>12.9±1.4***</td>
</tr>
<tr>
<td>200 mM NaCl</td>
<td>91.0±1.1***</td>
<td>69.9±0.3***</td>
<td>17.2±1.9****</td>
</tr>
</tbody>
</table>
Lipid digestion of gel digesta in the intestine

(Guo et al., 2016, Food Hydrocolloids)
Gastric emptying; rate of lipid digestion and absorption

- Structures/physical properties
- Absorbable nutrients
Food proteins

- Milk
- Meat
- Egg
- Soya
- Legumes
- Cereals
- Rice
Not all proteins are created equal nutritionally

Amino Acids in the Human Body

Composition:

**Essential Amino Acids**
- Isoleucine
- Leucine
- Valine
- Histidine
- Lysine
- Methionine
- Phenylalanine
- Threonine
- Tryptophan

**Non-Essential Amino Acids**
- Alanine
- Arginine
- Aspartic Acid
- Glutamic Acid
- Glycine
- Cysteine
- Glutamine
- Proline
- Serine
- Tyrosine

Differences in bioavailability of amino acids from different proteins
Protein digestibility

- Bovine Meat
- Cheese
- Rice
- Eggs
- Milk, Whole
- Poultry Meat
- Demersal Fish
- Mutton & Goat Meat
- Wheat
- Soybeans
- Potatoes
- Maize
- Peas
- Nuts
- Barley
- Millet
- Rye
- Sorghum
- Beans
- Oats
Plant-based proteins are generally of lower quality than animal-based proteins

- fibre
- anti-nutritional factors
- different structures
- Differences in bioavailability and digestibility of amino acids
Structure of dairy products affect the kinetics of protein digestion and amino acid bioavailability

Plasma leucine concentration (lmol/L) over a 7 h-period after ingestion of acid gel (AG) and rennet gel (RG), in minipigs. At a given time, differences between matrices are evidenced by different letters a, b (P < 0.05).
Ovalbumin aggregates formed under different conditions

Microstructure of OVA aggregates analyzed by TEM
Aggregate particle size distributions obtained by SLS and DLS

Nyemb et al., Food Chemistry, 2014
Protein digestion is affected by the aggregate morphology

Gastric conditions (pH 2.5)  Intestinal conditions (pH 6.5)

Nyemb et al., Food Chemistry, 2014
Mean fasting and postprandial responses to rye and wheat products over 180 min ($n = 20$). Postprandial responses to whole-kernel rye bread (a), β-glucan rye bread (b), and pasta (c) were significantly different from those to white wheat bread, $P < 0.05$.

Rice Processing and Starch Digestion
Starch Hydrolysis Differs for Fully Cooked, Partially Cooked and Uncooked Rice
Starch Hydrolysis Differs for Cooked Whole Rice and Cooked Rice Paste

Changes in starch hydrolysis (%) of homogenised (a) and non-homogenised (b) uncooked and cooked rice during in vitro gastro-small intestinal starch digestion. U (uncooked), PC (partially cooked), FC (fully cooked)

Tamura et al., 2016
Native Microstructure of Beans and In vitro Starch Digestion

Starch Hydrolysis Differs for Whole Beans, Bean Flour and Bean Starch

Whole Navy Beans

Berg et al., 2012
Microstructure of Bean Cotyledon Cells During and After Digestion
Intact Cotyledon Cells in Whole Navy Beans

Un-digested

30 min Gastric

10 min Small Intestine

Berg et al., 2012

120 min Small Intestine
Plant food legume materials

Adzuki beans

Lima beans

Chickpeas

Navy beans

Lentils
Preliminary results
Morphology of isolated legume cells by light microscopy

Chickpea
Lima bean
Adzuki bean
Lentil
Navy bean
Preliminary results

Chemical composition of legume cells

- Starch content (w/w)
  - Lima bean 56.53 ± 1.02
  - Navy bean 51.44 ± 2.24
  - Chickpea 60.97 ± 1.08

- Moisture content, protein, lipids, carbohydrates, ash

- Cell wall
  - Cellulose
  - Xyloglucan
  - Pectin
Preliminary results

*In vitro* starch digestion of navy bean cotyledon cells

![Graph showing starch hydrolysis over time for different samples: Waxy corn starch, Cooked potato starch, Cooked navy bean, and Uncooked cotyledon cell.](chart.png)
Concluding Remarks

> Further establish the role of food matrix in nutrition (consider food matrix as a variable in nutrition studies)

> Understanding the behaviour of food structures/matrices in the GIT

> Establish responses of GIT to different material structures, including modelling

> Develop more complex in vitro models for studying digestion and nutrient liberation

> Validation of *in-vitro* models using *in-vivo* studies

> Strong inter-disciplinary approach, involving physics, chemistry, colloid science, process engineering, biology and nutrition.
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Thank you!
Amino acid digestibility reflects enzymatic hydrolysis and microbial fermentation of ingested proteins and peptides and absorption of AA and peptides from the gastrointestinal lumen (Fuller, 2003).

Bioavailability of dietary AA is defined as the proportion of ingested dietary AA that is absorbed in a chemical form that renders these AA potentially suitable for metabolism or protein synthesis (Lewis and Bayley, 1995).
Key Steps of Lipid Digestion and Absorption

**STEP 2**
Pancreas releases:
- Lipase (+colipase)
- Cholesterol esterase
- Phospholipase A\(_2\)

**STEP 3**
Liver releases bile acids to solubilize lipid products in mixed micelles

**STEP 4**
Lipids absorbed from micelles into epithelial cells

**STEP 5**
Chylomicrons form and travel through lymphatics

Lipids:
- Triacylglycerol
- Cholesterol esters
- Phospholipids