Carbohydrates, viscosity development, & extrusion efficiency

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Session Overview

Introduction
- Extrusion processing overview
- Operational controls & variables

How Ingredients Influence the Process
- Classification of ingredients based on functionality
- Research highlights in ingredient extrusion

How the Process Influences Ingredients
- Focusing on starch transformations
- Importance of viscosity in process efficiency & ingredient characterizations

Summary, Q & A

Why do we process pet food?

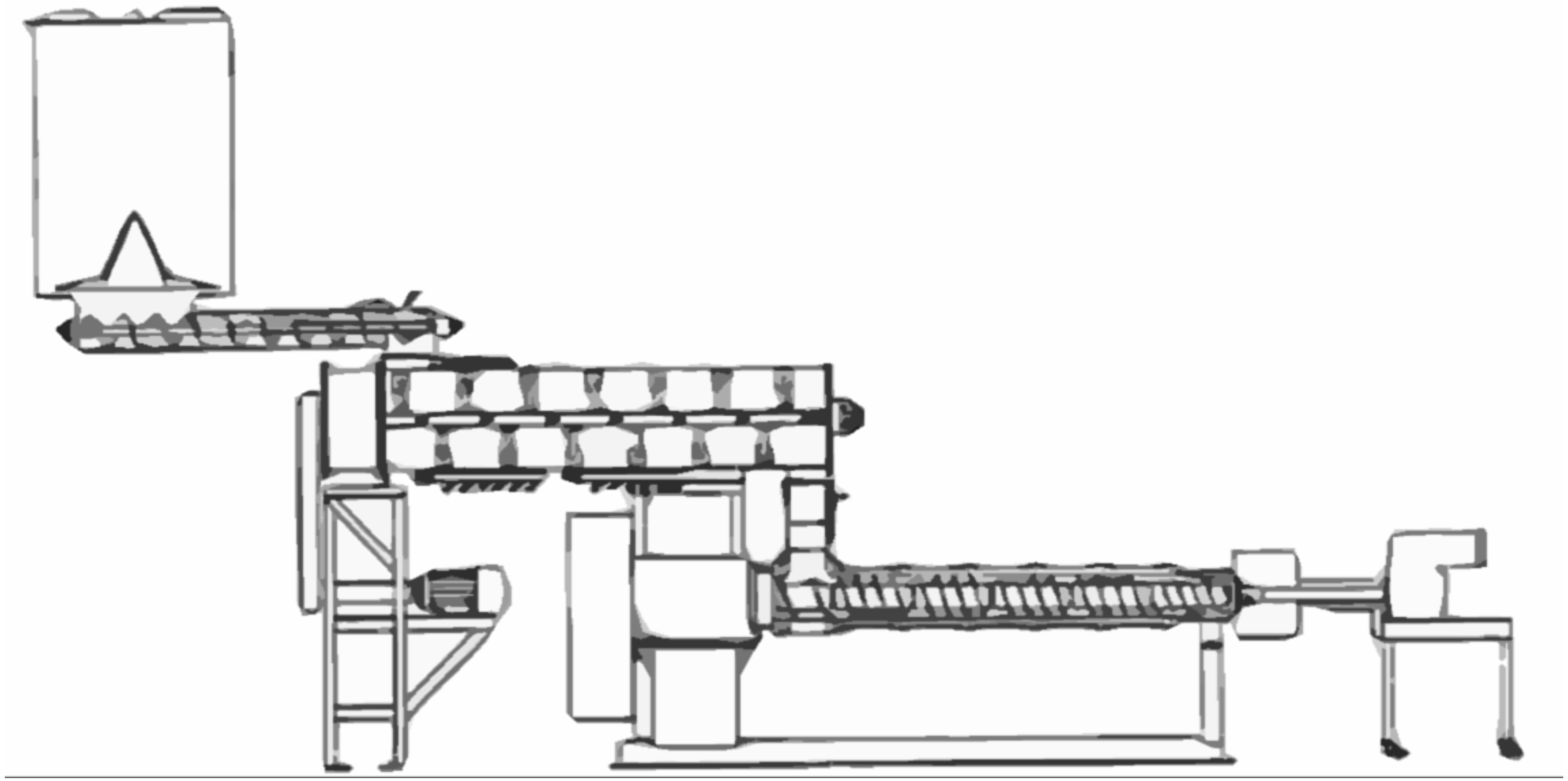
- Food safety
- Product differentiation
- Distribution efficiencies
- Shelf-stability
- Economics

What makes extrusion unique?

- Complex formulations with high number of raw material inputs
- Often complete nutrition - like infant formulas
- Ingredient types – both raw and processed
- Utilization of thermal + mechanical energy for cooking
- High-temperature, short-time process
- Shelf-stable (~12-24 months)

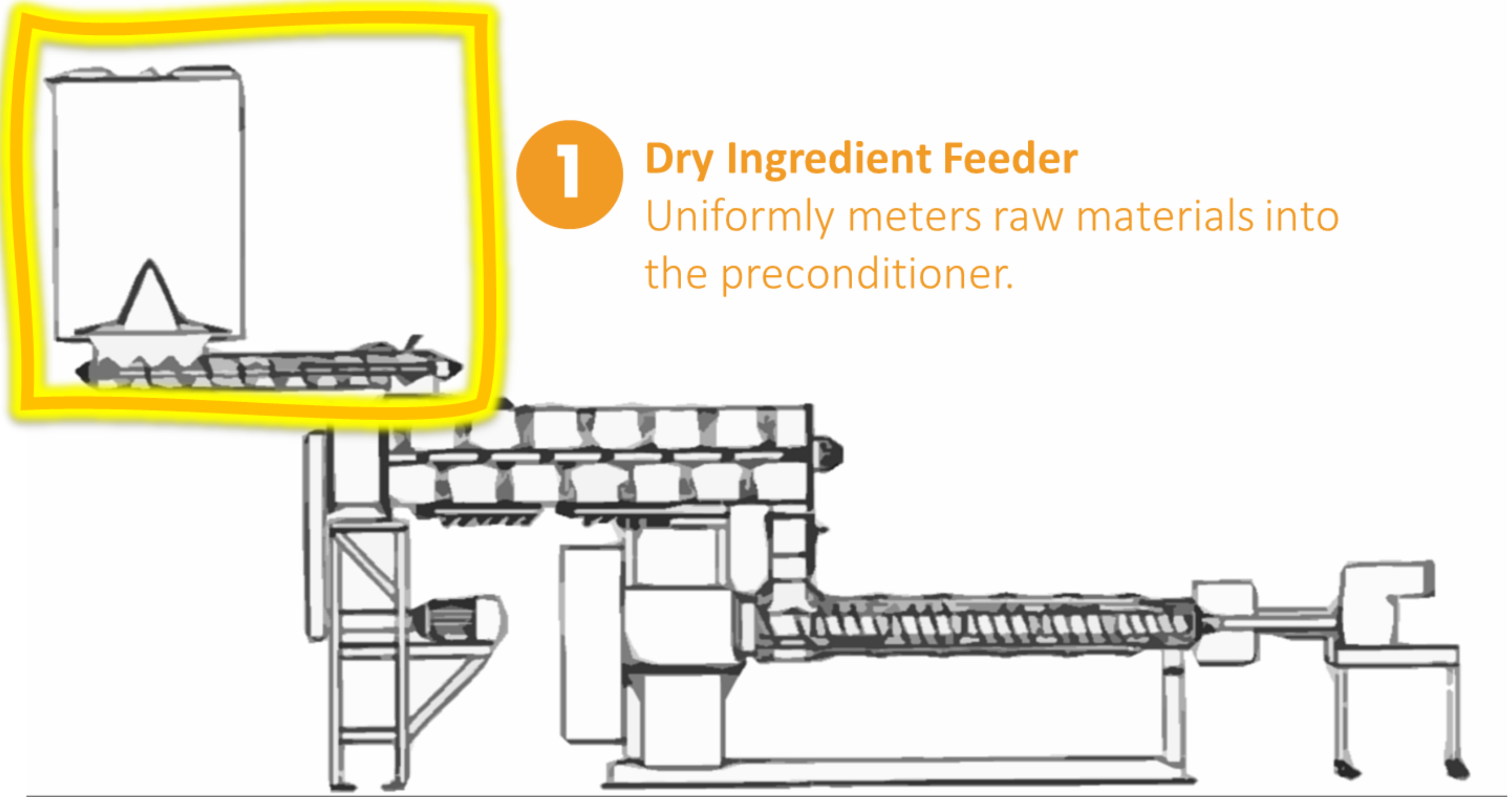
Extrusion Cooking Overview

Key System Elements



Extrusion Cooking Overview

Key System Elements

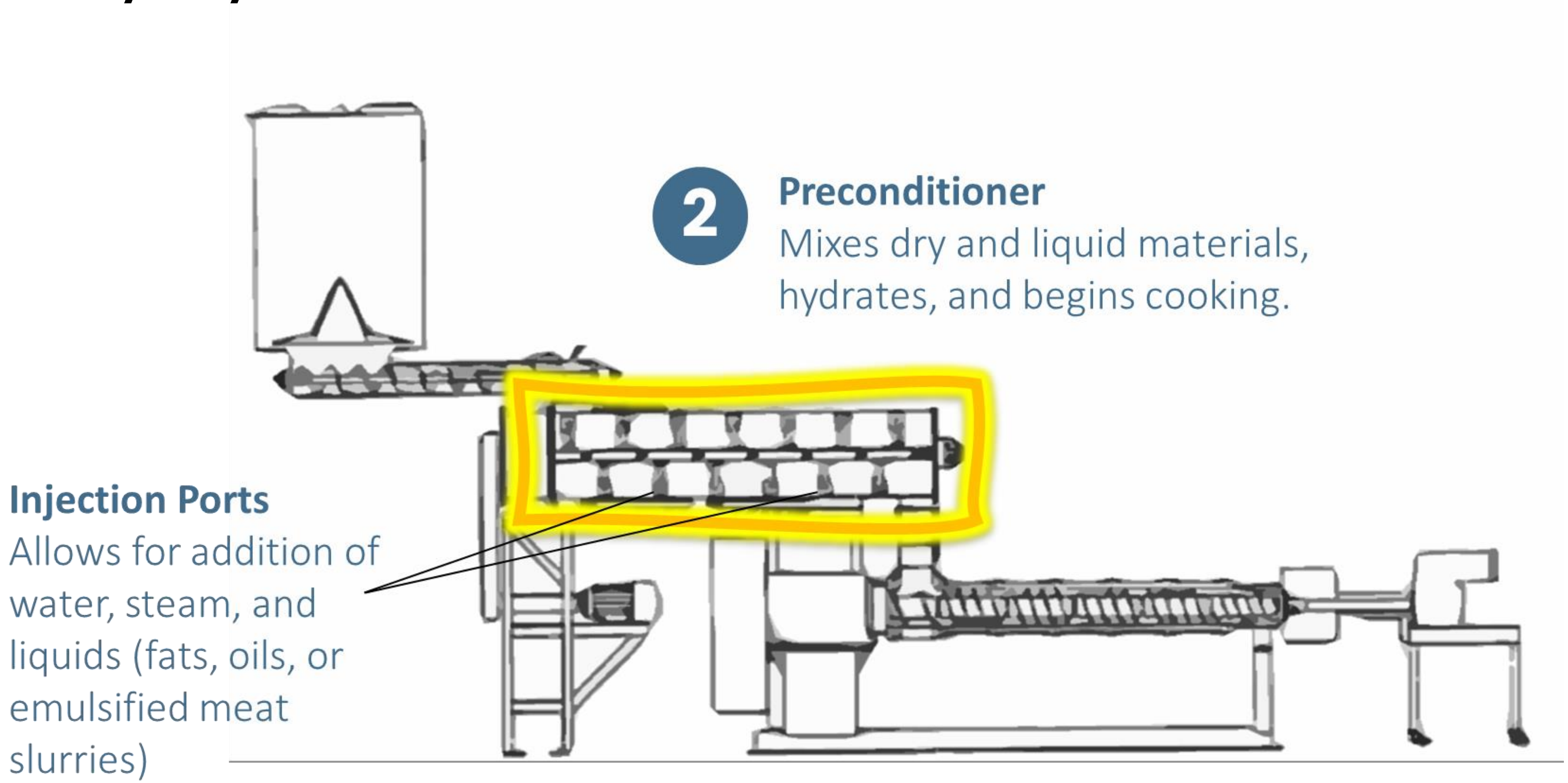


1 **Dry Ingredient Feeder**

Uniformly meters raw materials into the preconditioner.

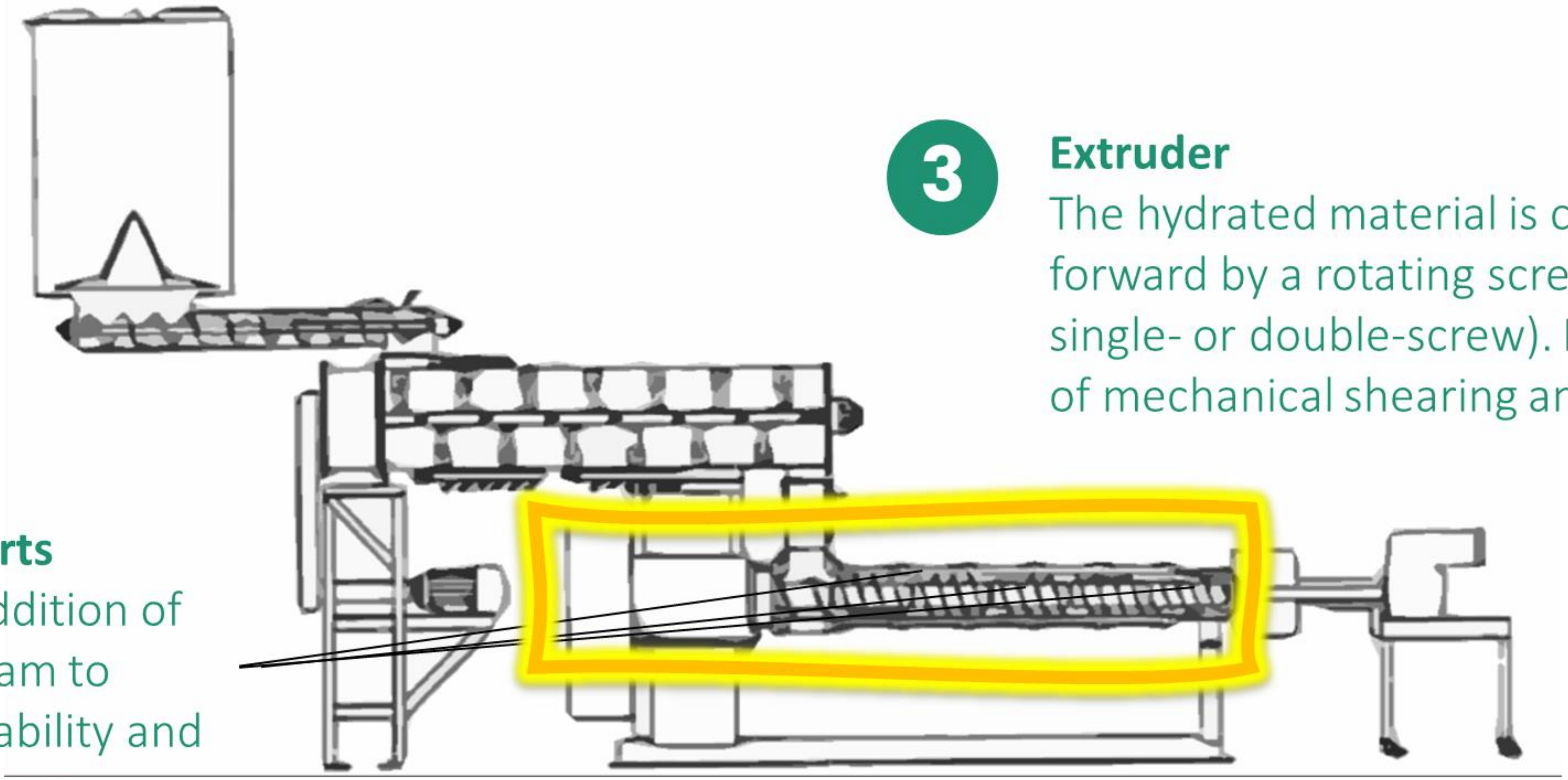
Extrusion Cooking Overview

Key System Elements



Extrusion Cooking Overview

Key System Elements



3 Extruder

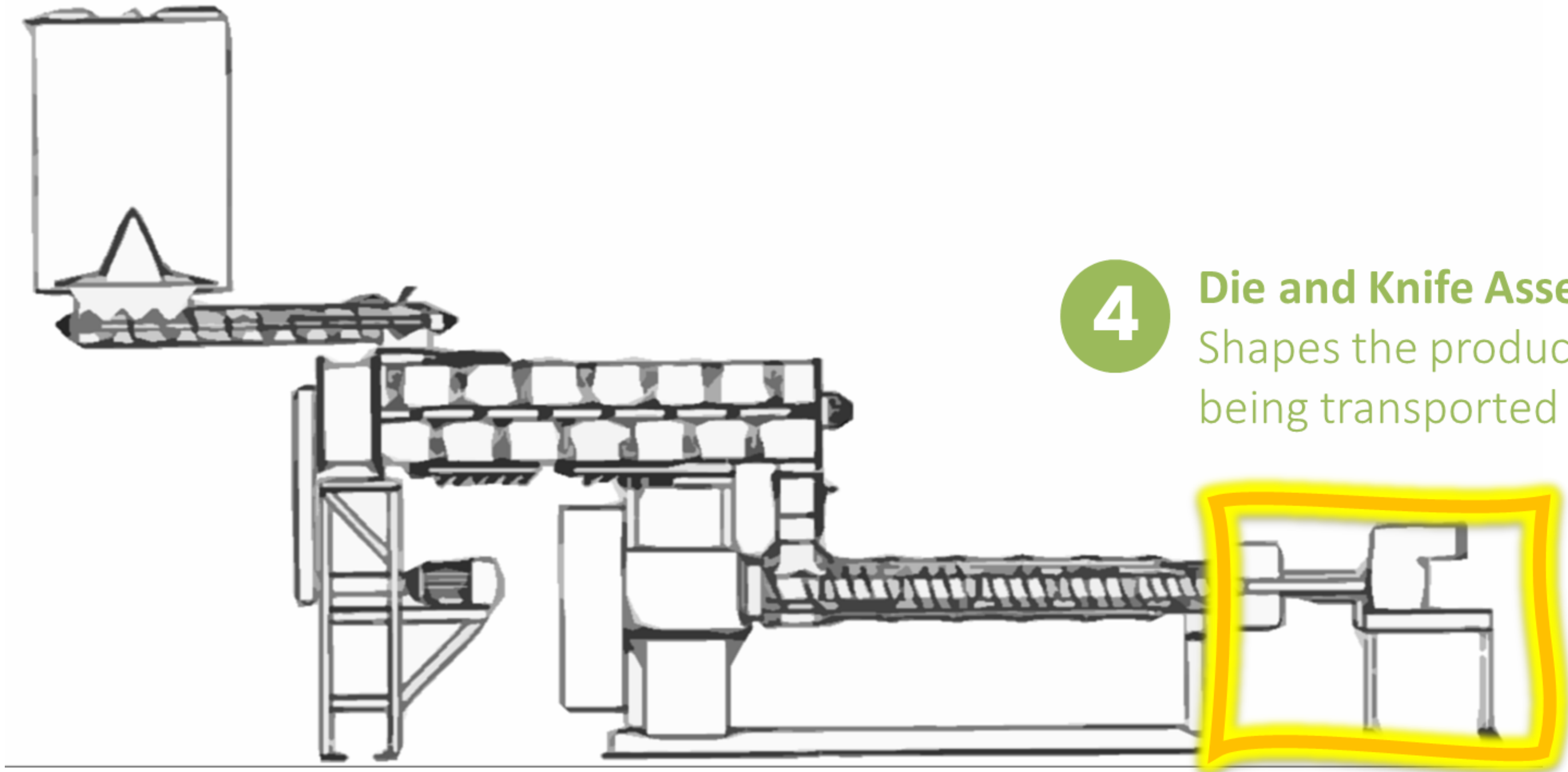
The hydrated material is conveyed forward by a rotating screw (may be single- or double-screw). Primary site of mechanical shearing and cooking.

Injection Ports

Allows for addition of water or steam to control flowability and cooking process.

Extrusion Cooking Overview

Key System Elements



4 **Die and Knife Assembly**
Shapes the product before being transported to the dryer.

Extrusion Cooking Overview

Key System Elements

1

Operator Controls
Fill Volume
Screw Speed

Effects
Feed Rate to Preconditioner

2

Operator Controls
Water Injection
Steam Injection
Screw Speed

Effects
Discharge Moisture
Feed Rate To Extruder

3

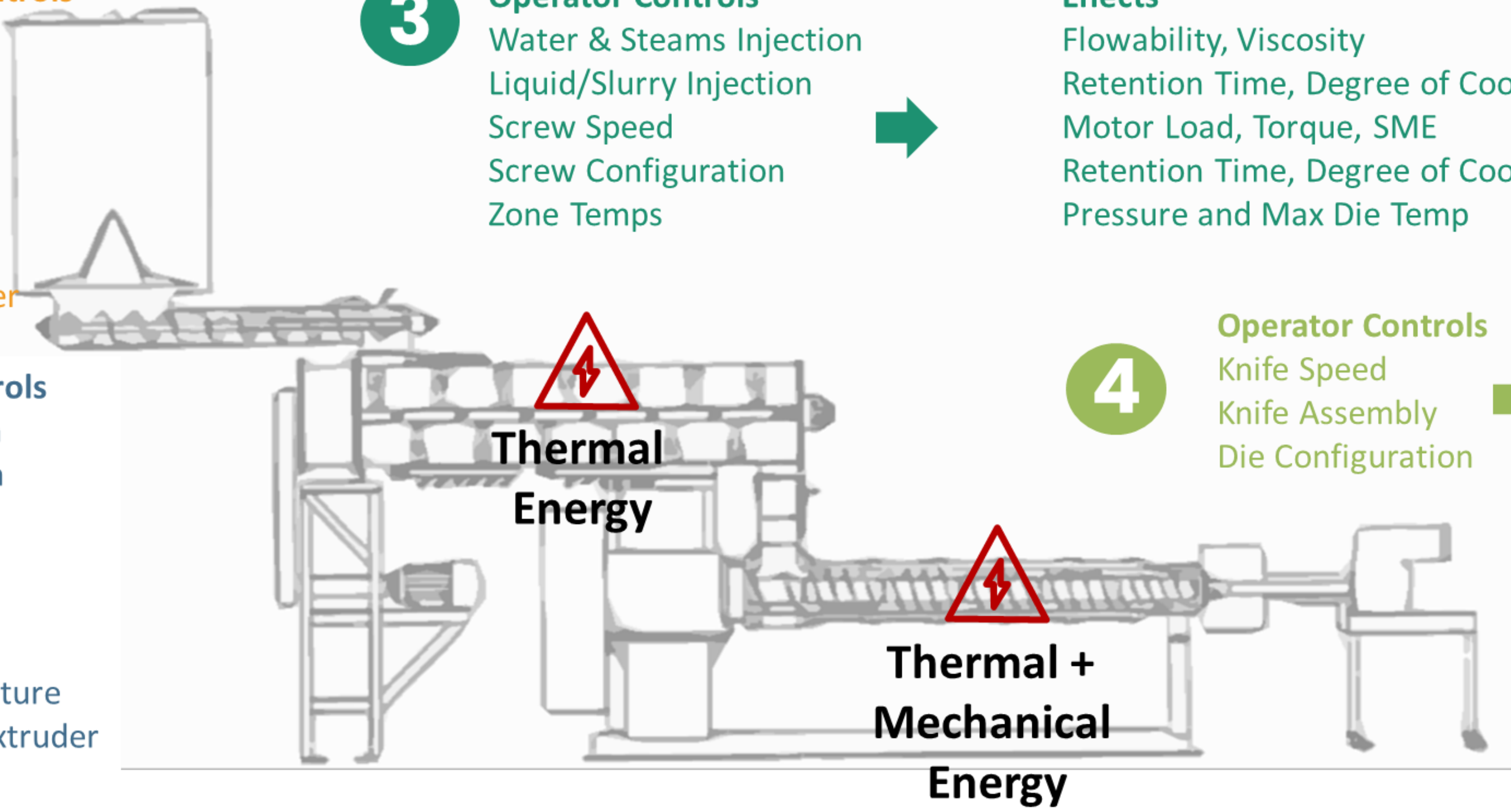
Operator Controls
Water & Steams Injection
Liquid/Slurry Injection
Screw Speed
Screw Configuration
Zone Temps

Effects
Flowability, Viscosity
Retention Time, Degree of Cook
Motor Load, Torque, SME
Retention Time, Degree of Cook
Pressure and Max Die Temp

4

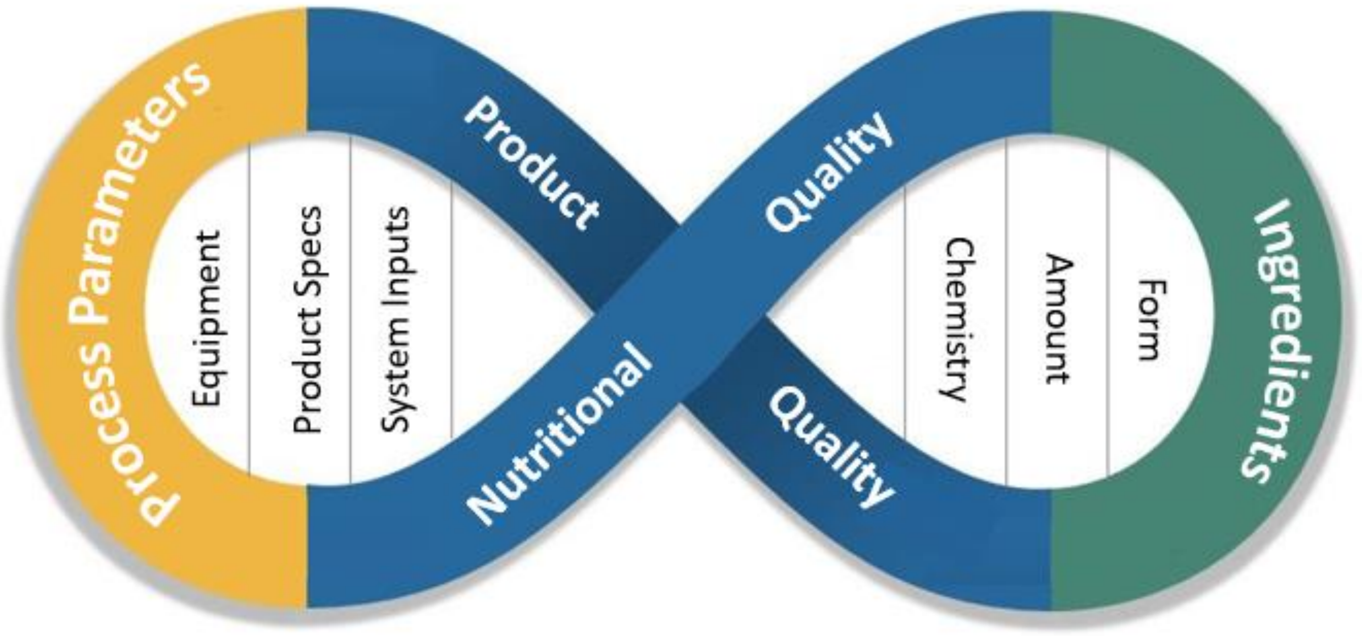
Operator Controls
Knife Speed
Knife Assembly
Die Configuration

Effects
Piece Shape
Cut Length
Piece Expansion
~Bulk Density



Processing & Ingredients are Interrelated

Extrusion process parameters depend on the ingredients being used, and how the ingredients are processed determine the chemical transformations occurring in the food. **Both must be balanced** to produce a product with **consistent nutritional, physical, and microbiological quality specifications**.



How Ingredients Influence The Process

Raw Material Selection
key deciding factors

- Nutrition
- Processability
- Marketability
- Economic viability
- Product uniformity and texture
- Product palatability
- Shelf-life
- Sustainability

Guy Classification System
grouping based on functionality

Classification Groups

1. Structure-Forming Materials
2. Dispersed-Phase Filling Materials
3. Plasticizers and Lubricants
4. Soluble Solids
5. Nucleating Substances
6. Coloring Substances
7. Flavoring Substances

The Premise:

Ingredients possess different functional properties for extrusion applications.

Practical Application:

By understanding the characteristics of biopolymers under extrusion conditions, we can start to understand why certain ingredients affect the process in different ways.

REFERENCE:
R. Guy (2001). Guy, R. Raw materials for extrusion cooking. In *Extrusion Cooking*; Woodhead Publishing: Sawston, UK, 2001; pp. 5–28. Campden and Chorleywood Food Research Association.

Guy Classification System

grouping based on functionality

	Group	Characteristics	General Effects in Extrusion
1	Structure-Forming Materials	Polymers with film-forming ability that withstands the expansion of water vapor on exiting the extruder.	May Increase or Decrease Expansion May Increase or Decrease Moisture Req. May Increase or Decrease Thermal Req. May Increase or Decrease Viscosity
2	Dispersed-Phase Filling Materials	Proteins and fibrous materials located within the continuous starch structure. physical presence disrupts the cell walls of structure-forming film.	Decrease Expansion Increase or Decrease Moisture Req
3	Plasticizers and Lubricants	Transforms polymers from solids to deformable plastic fluids. Plasticizers reduce the dissipation of mechanical energy and reduces the heat input. Lubricants reduce the applied shear forces within the dough mass and along the metal surfaces of the screw and barrel.	Increase Bulk Density Decrease Expansion Decrease Frictional Heat Decrease Specific Mechanical Energy
4	Soluble Solids	low molecular weight materials, such as sugars or salts, may be added to a recipe for flavoring or humectant properties.	Reduces Melt Viscosity & Retention Time Increase Water Holding Capacity
5	Nucleating Substances	Increase the number of bubbles present in the expanding extrudate	Increase Expansion
6	Coloring Substances	Contribute to color in the extrudates.	Little to no effect
7	Flavoring Substances	Contribute to flavor formation in thermal reactions.	Little to no effect

Plant & Animal Protein Sources

particle size influences product characteristics

Background

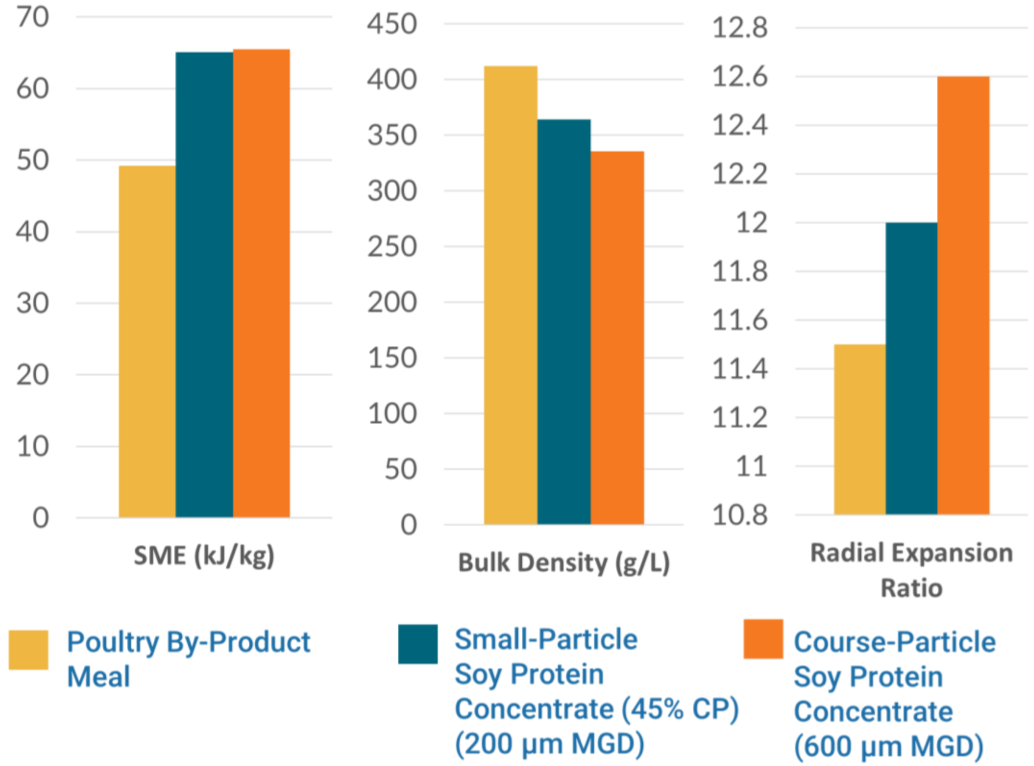
- Plant protein concentrates have high digestibility, good amino acid profile, low ash content, adequate palatability and desirable processing characteristics.
- Different particle grind sizes are commercially available, but data is limited on how this affects extrusion.

Highlights

- Course soybean meal particle size replacing 45% of the total protein resulted in higher SME and radial expansion.
- Animal-protein required less SME to process, resulted in a higher bulk density, and lower radial expansion relative to SBM.

Proximate Composition of Test Diets

Composition	Poultry By-Product Meal	Soy Protein Concentrate (45% of CP; small particles)	Soy Protein Concentrate (45% of CP; course particles)
Dry Matter, %	91.4	92.7	94.0
Crude Protein, %	63.9	62.4	60.5
Crude Fat, %	13.7	0.4	0.4
Starch, %	-	0.5	0.5
Crude Fiber, %	-	4.6	2.9
Ash, %	13.1	6.9	7.7



REFERENCE

Venturini, K. S., Sarcinelli, M. F., Baller, M. A., Putarov, T. C., Malheiros, E. B., & Carciofi, A. C. (2018). Processing traits and digestibility of extruded dog foods with soy protein concentrate. Journal of Animal Physiology and Animal Nutrition, 102(4), 1077–1087. https://doi.org/10.1111/jpn.12894 - Sao Paulo, Brazil

Effects of Dehulled Faba Beans
adjust for hydration rate & expansion properties

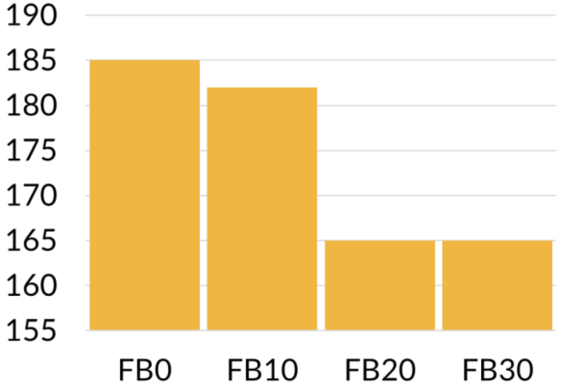
Background

- Four experimental petfood diets containing 0, 10, 20, or 30% inclusion of dehulled Faba beans processed to maintain the same bulk density of the finished product.
- Inclusion of test ingredient was at the expense of corn gluten meal and rice.

Faba bean Composition	
Dry Matter, %	89.3
Crude Protein, %	30.8
Crude Fat, %	1.75
Crude Fiber, %	0.42
Ash, %	3.30
NFE*, %	53.03
SCO*, %	6.83

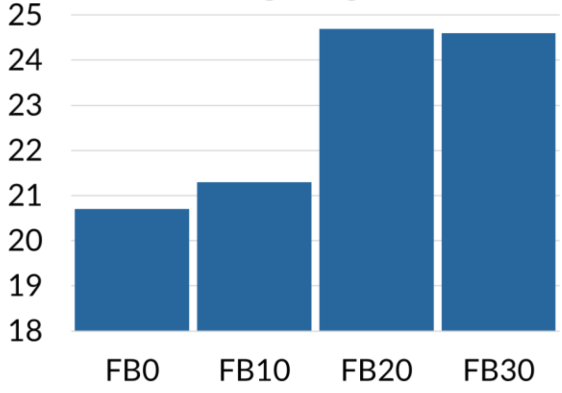
*NFE = Nitrogen-Free Extract; SCO = Short Chain Oligosaccharides (Sucrose + raffinose + stachyose + verbascose)

Highlights



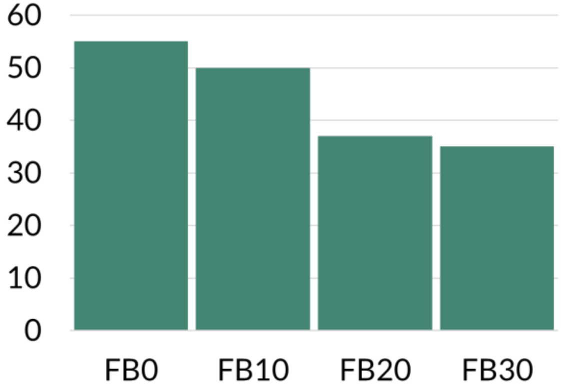
PC Speed (rpm)			
FB0	FB10	FB20	FB30
185	182	165	165

- As Faba bean inclusion increased, the retention time in the preconditioner needed to be increased to allow more time for material hydration.



PC Water (kg/hr)			
FB0	FB10	FB20	FB30
20.7	21.3	24.7	24.6

- As Faba bean inclusion increased, water flow in the preconditioner increased to sufficiently hydrate the material before extrusion.



Mass Restriction Valve, %			
FB0	FB10	FB20	FB30
55	50	37	35

- As Faba bean inclusion increased, MRV opening decreased to improve expansion on exiting the extruder.

REFERENCE

Corsato Alvarenga, Isabella, and Charles Gregory Aldrich. "The Effect of Increasing Levels of Dehulled Faba Beans (Vicia faba L.) on Extrusion and Product Parameters for Dry Expanded Dog Food." vol. 8,1 26. 12 Jan. 2019, doi:10.3390/foods8010026

Ancient Grains vs. Grain-Free

swelling power & mechanical energy

Background

- Two maintenance dog diets containing the same proportion (50%) of carbohydrate sources: 1) ancient grain diet with spelt, millet, and sorghum; and 2) grain-free diet with potato, peas, and tapioca starch were extruded to produce the same target bulk density out of the extruder.

Proximate Composition of Test Diets

Composition	Ancient Grains	Grain-Free
Moisture, %	5.41	5.49
Crude Protein, %	37.00	38.00
Crude Fat, %	15.80	12.50
Total Dietary Fiber, %	6.91	10.07
Insoluble Fiber, %	5.25	3.85
Soluble Fiber, %	1.66	6.22
Total Starch, %	38.04	35.32
Ash, %	4.24	4.33

Process Parameters & System Variables

	Ancient Grain	Grain-Free
Preconditioner Steam, kg/hr	14.46	5.5
Extruder Screw Speed, rpm	442	637
Specific Mechanical Energy, kJ/kg	115	141
Kibble Traits		
Sectional Expansion Index	3.03	3.50
Hardness, kg	3.12	6.36

Highlights

- PC Steam was decreased for the GF diets to high swelling power of tuber starches compared to cereal grains.
- Extruder screw speed was increased to lower the viscosity and improve flowability of the GF diet.
- Higher SME in GF was due to higher screw speed and lower feed rate. Increased hardness was attributed to the higher SME.
- GF expanded more than AG.
- GF kibbles were harder than AG.

REFERENCE

Pezzali, Julia Guazzelli, and Charles Gregory Aldrich. “Effect of Ancient Grains and Grain-Free Carbohydrate Sources on Extrusion Parameters and Nutrient Utilization by Dogs.” Journal of Animal Science, vol. 97, no. 9, Oxford University Press, 2019, pp. 3758–67, doi:10.1093/jas/skz237.

Comparison of Fiber Sources

soluble:insoluble fractions & particle size matter

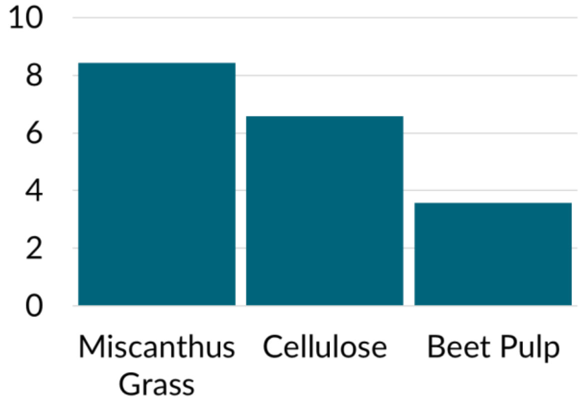
Background

- Three experimental petfood diets containing 10% inclusion of MC, BP, or CE processed to maintain the same bulk density of the finished product (330 g/L)

Fiber Profiles of Test Ingredients

Composition	Miscanthus Grass	Cellulose	Beet Pulp
Dry Matter, %	95.0	95.30	92.53
Crude Fiber, %	47.6	76.3	20.2
Total Dietary Fiber, %	90.0	102.6	62.4
Insoluble Fiber, %	82.7	100.0	36.0
Soluble Fiber, %	7.3	2.6	26.4
Geometric Mean Diameter, µm	103.5	77.3	193.8

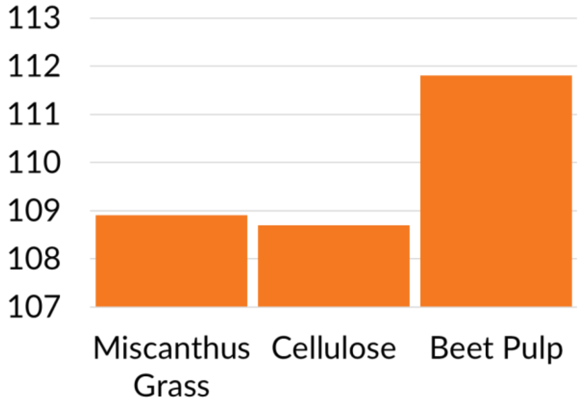
Highlights



Kibble Diameter Shrinkage (%)

Miscanthus Grass	Cellulose	Beet Pulp
8.43	6.58	3.58

- Larger Miscanthus grass fiber particles may have disrupted the starch matrix to a greater extent than cellulose leading to weakened cell structures on drying.
- Lower TDF and higher soluble fraction in BP may explain the structure disrupting effects of MG in comparison.



SME (kJ/kg)

Miscanthus Grass	Cellulose	Beet Pulp
108.9	108.7	111.8

- High soluble fibers can increase the viscosity of the melt inside the barrel, resulting in greater SME for the diet with beet pulp.

REFERENCE

Donadelli, Renan A, Hulya Dogan, and Greg Aldrich. The Effects of Fiber Source on Extrusion Parameters and Kibble Structure of Dry Dog Foods. *Animal feed science and technology* 274 (2021): 114884.

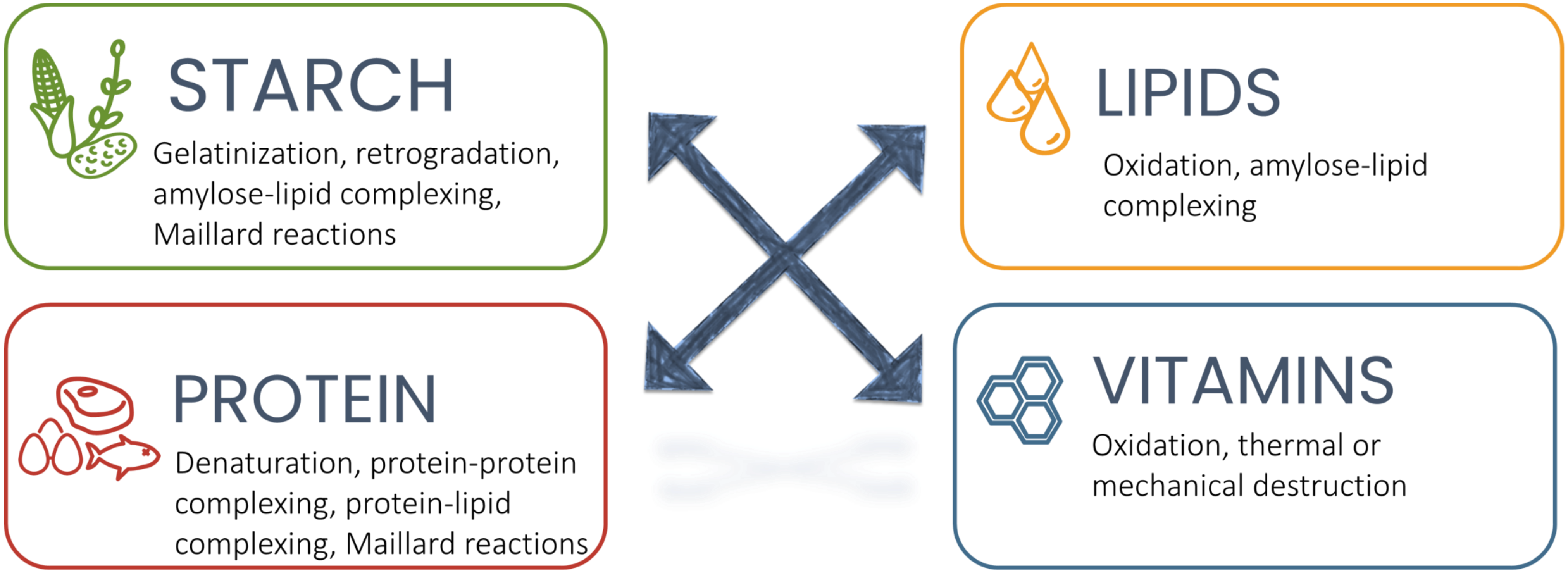
How the Process Influences Ingredients

Chemical Changes Occurring to Ingredients During Extrusion

- Cleavage of polymers
  - exposes functional groups for reactions
- Recombination and complexing
  - formation of new compounds
- Thermal and mechanical degradation
  - Influences bioavailability & increases losses

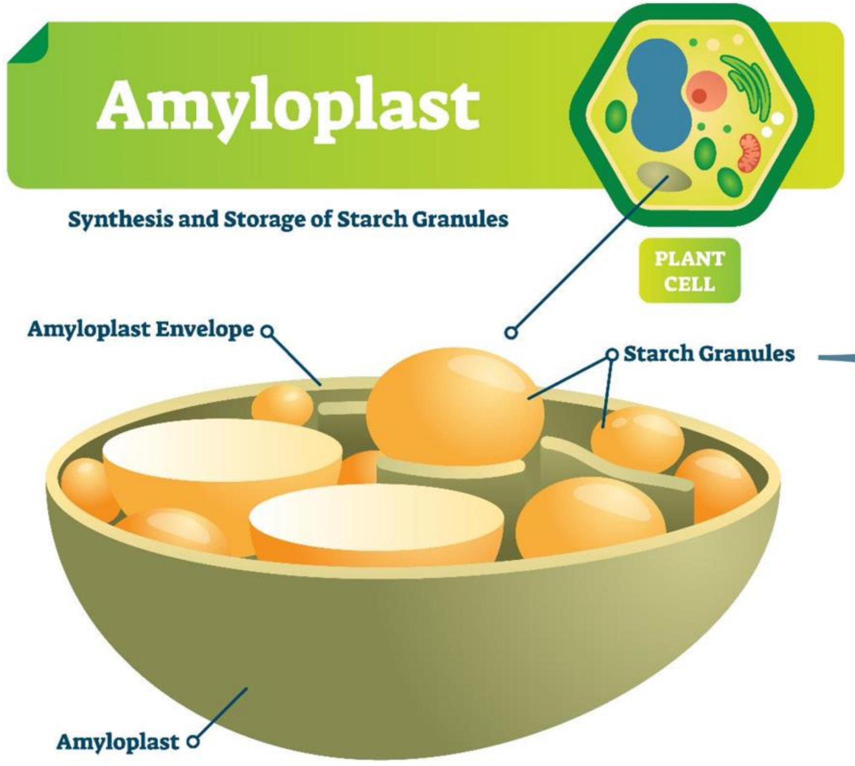
Major Nutrient Classes

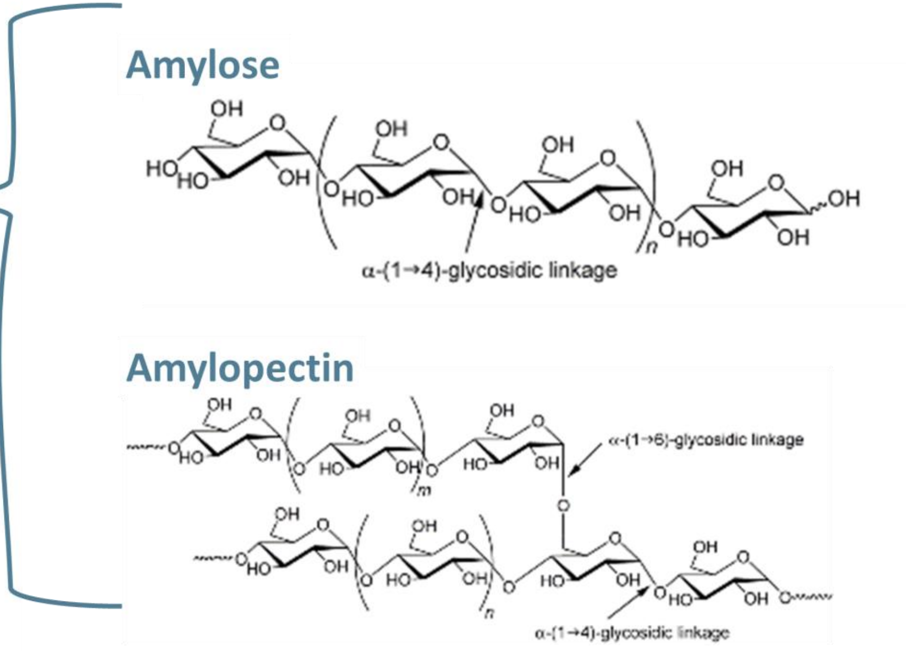
key reactions occurring during extrusion



Basics of Starch Composition

foundation for chemical transformations





Basics of Starch Composition

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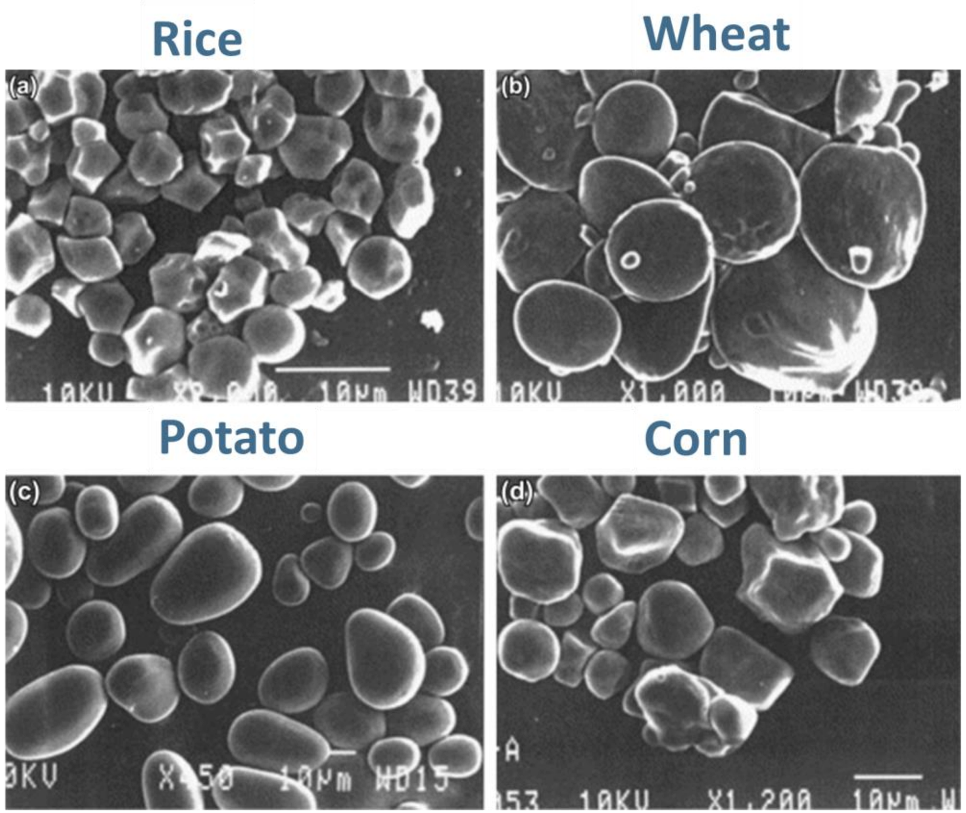
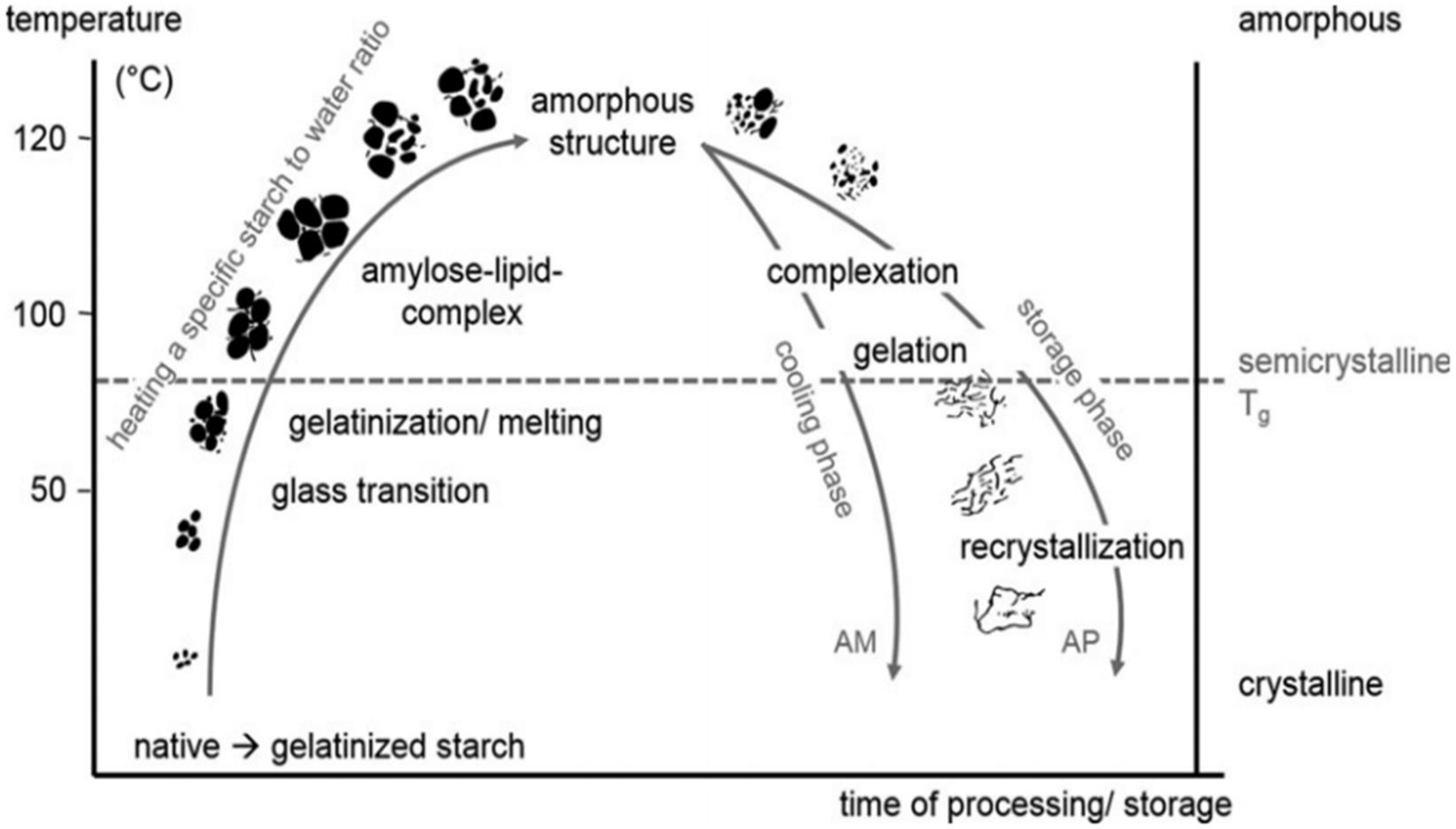


Starch granule size differs considerably among source and ranges from 1 to 110 µm.

Starch Source	Amylose, %	Amylopectin, %
Waxy Corn Starch	< 1	> 99
Waxy Rice Starch	2	98
Chickpea Starch	14	86
Tapioca	15 - 35	85 - 65
Potato Starch	20	80
Rice Starch	20	80
Sweet Potato Starch	20 - 30	70 - 80
Wheat Starch	24	76
Lentil Starch	25	50
Corn Starch	25	75
Pea Starch	30 - 80	20 -70
High-Amylose Corn Starch	70	30

REFERENCE:
Singh, N., Singh, J., Kaur, L., Singh Sodhi, N., & Singh Gill, B. (2003). Morphological, thermal and rheological properties of starches from different botanical sources. *Food Chemistry*, *81*(2), 219–231. https://doi.org/10.1016/S0308-8146(02)00416-8

Starch Transformations
related to amylose:amylopectin ratio



REFERENCE:
Schirmer, Markus, et al. “Starch Gelatinization and Its Complexity for Analysis.” Starch - Stärke, vol. 67, no. 1-2, Blackwell Publishing Ltd, 2015, pp. 30–41, doi:10.1002/star.201400071.

Starch Transformations

related to amylose:amylopectin ratio

Starch Source	Amylose, %	Amylopectin, %
Molecular Structure	Mostly linear, α-1-4 glycosidic linkages	Highly branched, α-1-4 glycosidic linkages with α-1-6 branches
Molecular Weight	105 – 106 Daltons	107 – 109 Daltons
Digestibility (β-amylase)	100%	60%
Solubility	Low	High
Gelatinization Temp.	Low	High
Amylose-Lipid Complexing	Very High	None
Gel Formation	Firm, irreversible	Soft, reversible
Film-Forming Ability	Coherent	Not readily formed
Viscosity	Low	High
Shear Stability	Relatively Stable	Unstable
Retrogradation Rate	High	Low

REFERENCE:
Schirmer, Markus, et al. "Starch Gelatinization and Its Complexity for Analysis." Starch - Stärke, vol. 67, no. 1-2, Blackwell Publishing Ltd, 2015, pp. 30–41, doi:10.1002/star.201400071.

Starch Gelatinization

Improves starch digestibility

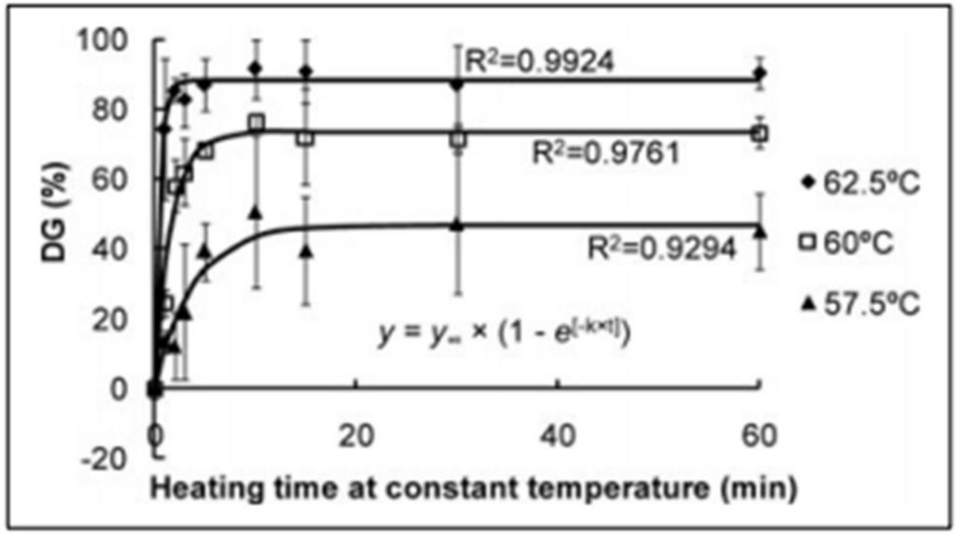
Gelatinization is:

the process of breaking down the intermolecular bonds of starch molecules in the presence of water and heat, allowing the hydrogen bonding sites to engage more water. This irreversibly dissolves the starch granule in water.

Gelatinization **requires**:

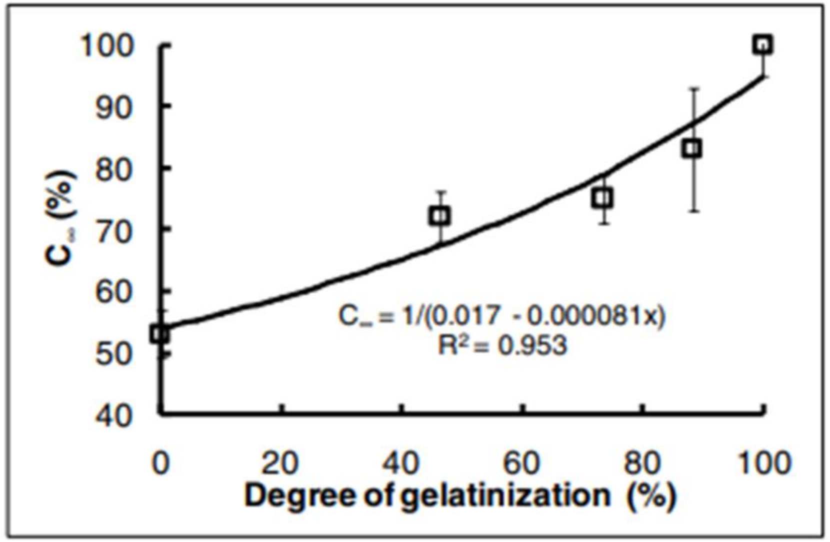
- Moisture
- Time
- Heat

- As temperature increases, the rate and degree of starch gelatinization increases.



Gelatinization Rate Potato Starch at Different Temperatures

- As degree of gelatinization increases, starch digestibility increases.



***In vitro* digestibility of potato starch as a function of gelatinization.**

REFERENCE:

Parada, Javier, and José M. Aguilera. "In Vitro Digestibility and Glycemic Response of Potato Starch Is Related to Granule Size and Degree of Gelatinization." *Journal of Food Science*, MS 20080550 Submitted 7/24/2008, Accepted 10/3/2008, vol. 74, no. 1, Blackwell Publishing Inc, 2009, pp. E34–E38, doi:10.1111/j.1750-3841.2008.01016.x.

Forming Resistant Starch

modifying the process to favor retrogradation

Resistant Starch

- Resistant to digestion by alpha-amylase in the small intestine;
- Possess fiber-like properties, and may offer similar health and functional properties in pet foods

FIVE TYPES

- **RS1 -** Physically entrapped starches (ex: coarsely ground raw grains)
- **RS2 -** Raw starch granules having a crystal structure resistant to digestive enzymes (ex: raw potato)
- **RS3 -** Retrograded starches formed from cooking and cooling
- **RS4 -** Chemically modified starches (ex: cross-linked starch)
- **RS5 -** Amylose-lipid complexed starch (ex: stearic acid-amylose complexes)

Process Parameters

Same formula produced two ways:

1) Low RS-Diet :
    - Smaller particle size (0.5 mm)
    - Higher PC Temperature (84° C P)
    - Reduce die opening (230 mm^2 ton/h), ↑ pressure
    - Higher SME (21.5 ± 0.54 kW-h/ton)
    - Higher Die Temp (112°C)
    - Higher degree of gelatinization (99.9%)

2) High RS-Diet
    - Larger particle size (2 mm)
    - Lower PC Temperature (59 °C)
    - Increased die opening (310 mm^2/ton/h), ↓ pressure
    - Lower SME t (11.6 ± 0.39 kW-h/ton)
    - Lower Die Temp (108°C)
    - Lower degree of gelatinization (62.6%)

Same Formula, Different Outcome:

Analysis of Test Diets

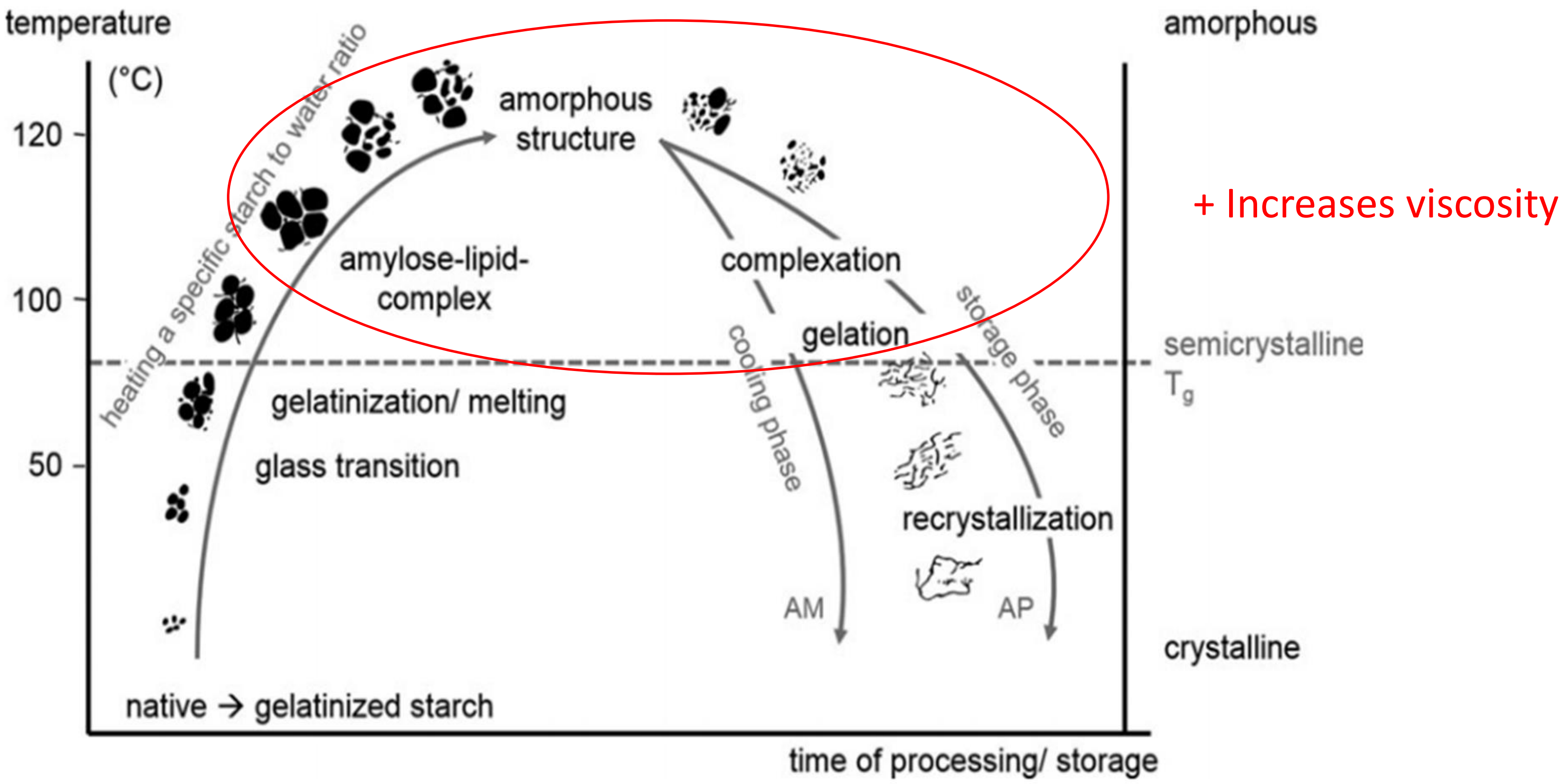
Composition	Low-RS Diet	High-RS Diet
Dry Matter, %	95.2	95.2
Crude Protein, %	26.6	26.6
Crude Fat, %	16.2	17.2
Crude Fiber, %	1.9	2.1
Ash, %	8.2	7.9
Starch, %	42.5	41.6
Resistant Starch, %	0.21	1.46
Bulk Density (g/L)	300	505

REFERENCE:

Peixoto MC, Ribeiro ÉM, Maria APJ, et al. Effect of resistant starch on the intestinal health of old dogs: Fermentation products and histological features of the intestinal mucosa. J Anim Physiol Anim Nutr. 2017;00:1—11. https://doi.org/10.1111/jpn.12711 - Sao Paulo, Brazil

Starch Viscosity Development

impacts process efficiency & product quality



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Starch Viscosity Development

impacts process efficiency & product quality

Viscosity is the resistance of a substance to flow, e.g. is a measure of the resistance of a fluid to deformation under shear stress.

Essentially, it can be thought of as the friction of liquid and it can in theory be calculated:

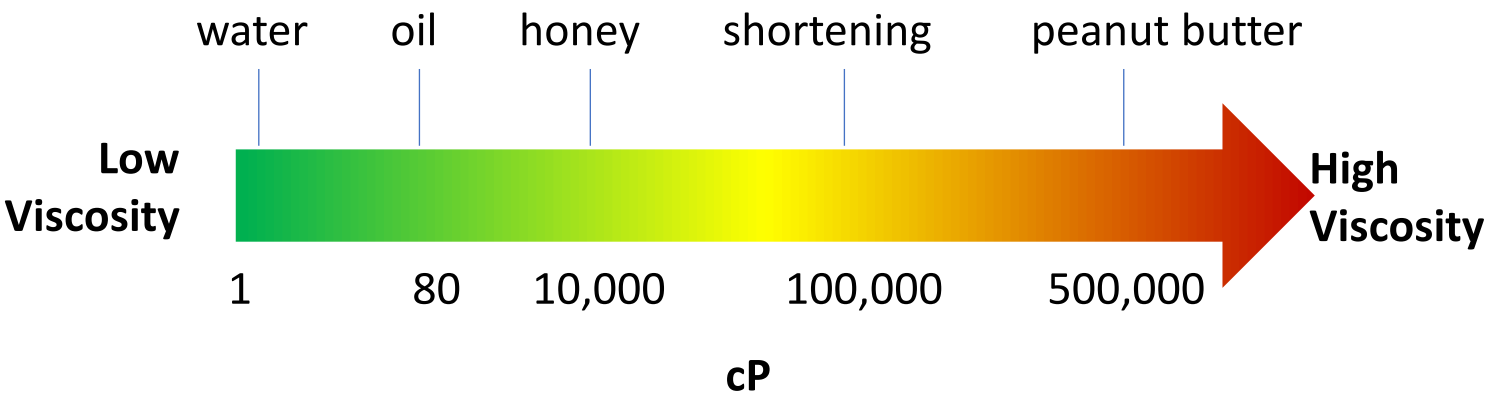
$\eta = \tau / \gamma$

Where :

(η) = viscosity
(τ) = *shear stress*
(γ) = *shear rate*

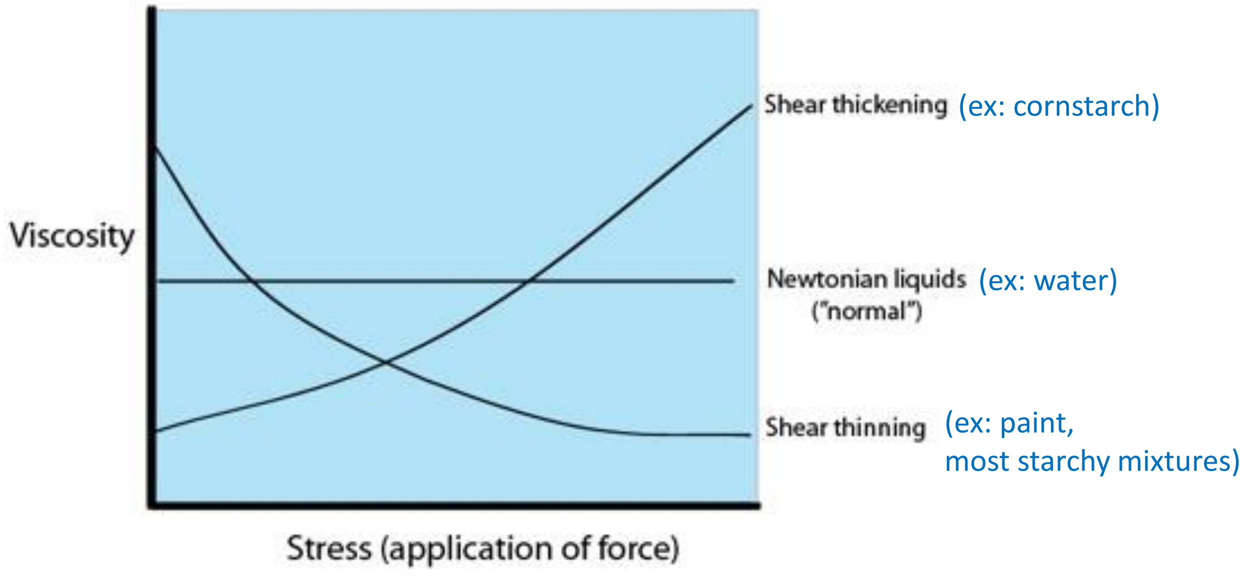
Units:
0.001 Pa•s = 1 mPa•s = 1 cP
(pascal sec) (millipascal sec) (centipoise)

Examples of Viscosity of Common Foods at Room Temperature



Starch Viscosity Development

impacts process efficiency & product quality



- Starchy mixtures under extrusion conditions exhibit non-Newtonian behavior, which results in reduction of viscosity as shear stress increases (also known as **sheer-thinning**).

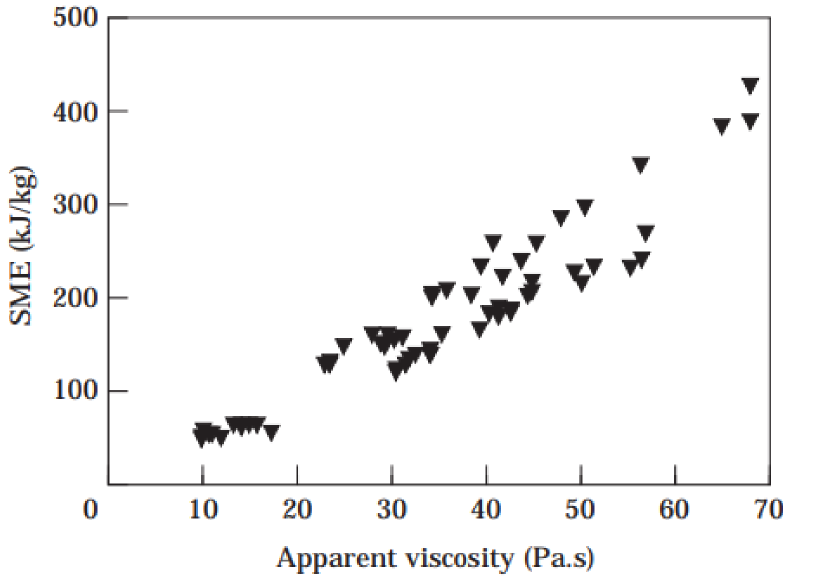


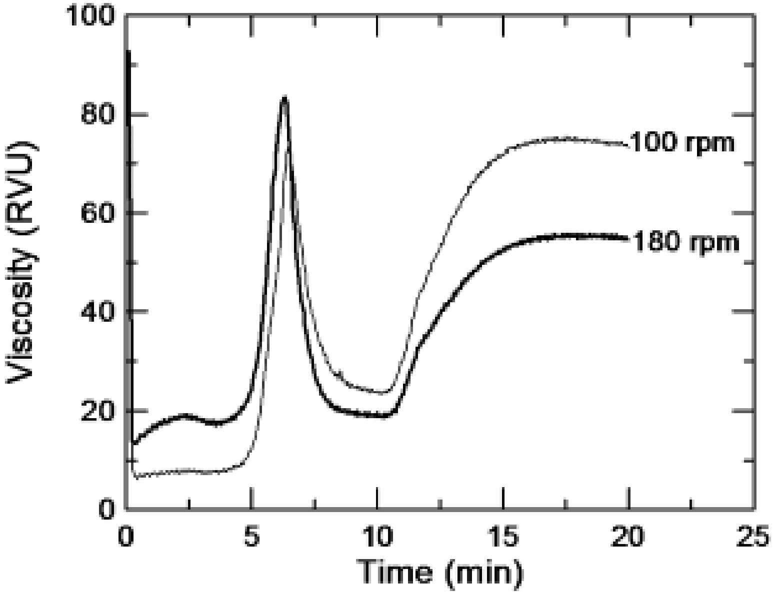
Fig. 7 Dependence of SME on apparent viscosity at 225 rpm screw speed

- As melt viscosity increases at constant screw speed, SME also increases since more mechanical energy per unit mass is needed to convey the material by the screw channels. In other words, if no adjustments are made to reduce viscosity, energy consumption will continue to increase.

REFERENCE:
Akdogan, H., Tomás, R.L., & Oliveira, J.C. (1997). Rheological Properties of Rice Starch at High Moisture Contents during Twin-screw Extrusion. Lwt - Food Science and Technology, 30, 488-496.

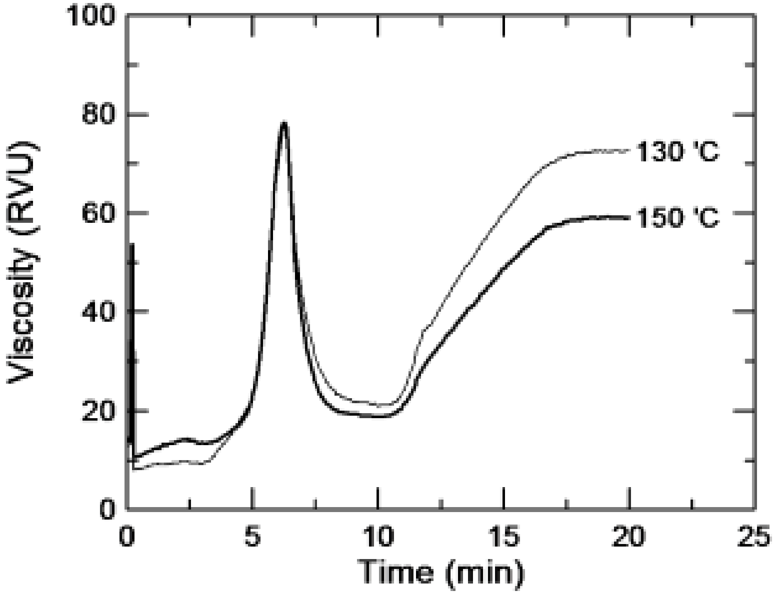
Controlling Viscosity
operational adjustments during processing

Effect of Screw Speed (Shear Rate)



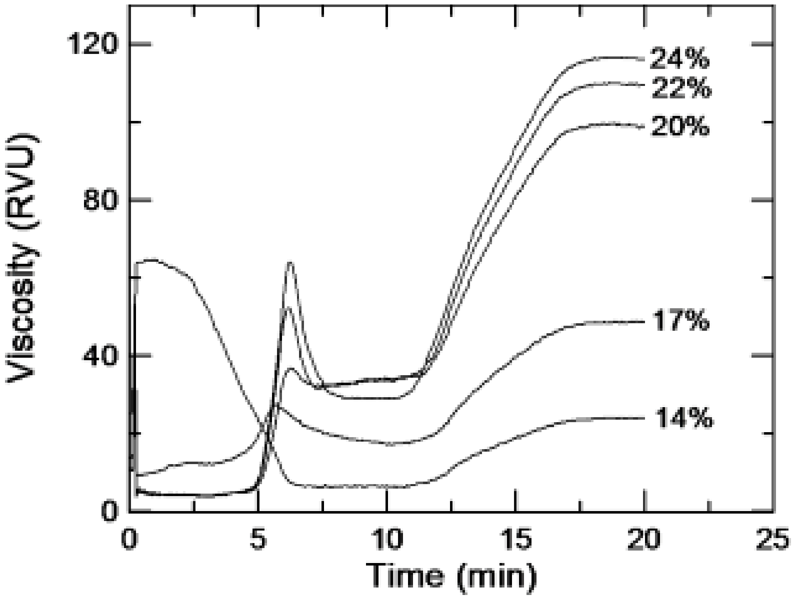
- Starches exhibit sheer-thinning behavior, causing a decrease in viscosity when screw speed (shear rate) is increased.

Effect of Temperature



- Starch viscosity decreases with higher temperatures.

Effect of Moisture Content



- Starch viscosity decreases with lower moisture contents. This is thought to be due to more complete degree of swelling and gelatinization under higher moisture conditions.

REFERENCE:
Whalen, P. J., Bason, M. L. and Booth, R. I. (1996). Measuring degree of cook in extruded foods using the Rapid Visco Analyser, Proc. 45th Aust. Cereal Chem. Conf., Y.A. Williams and C.W. Wrigley (eds.), Royal Aust. Chem. Inst. 289-293.

Viscosity Building in Extrusion

how to select starches based on viscous properties

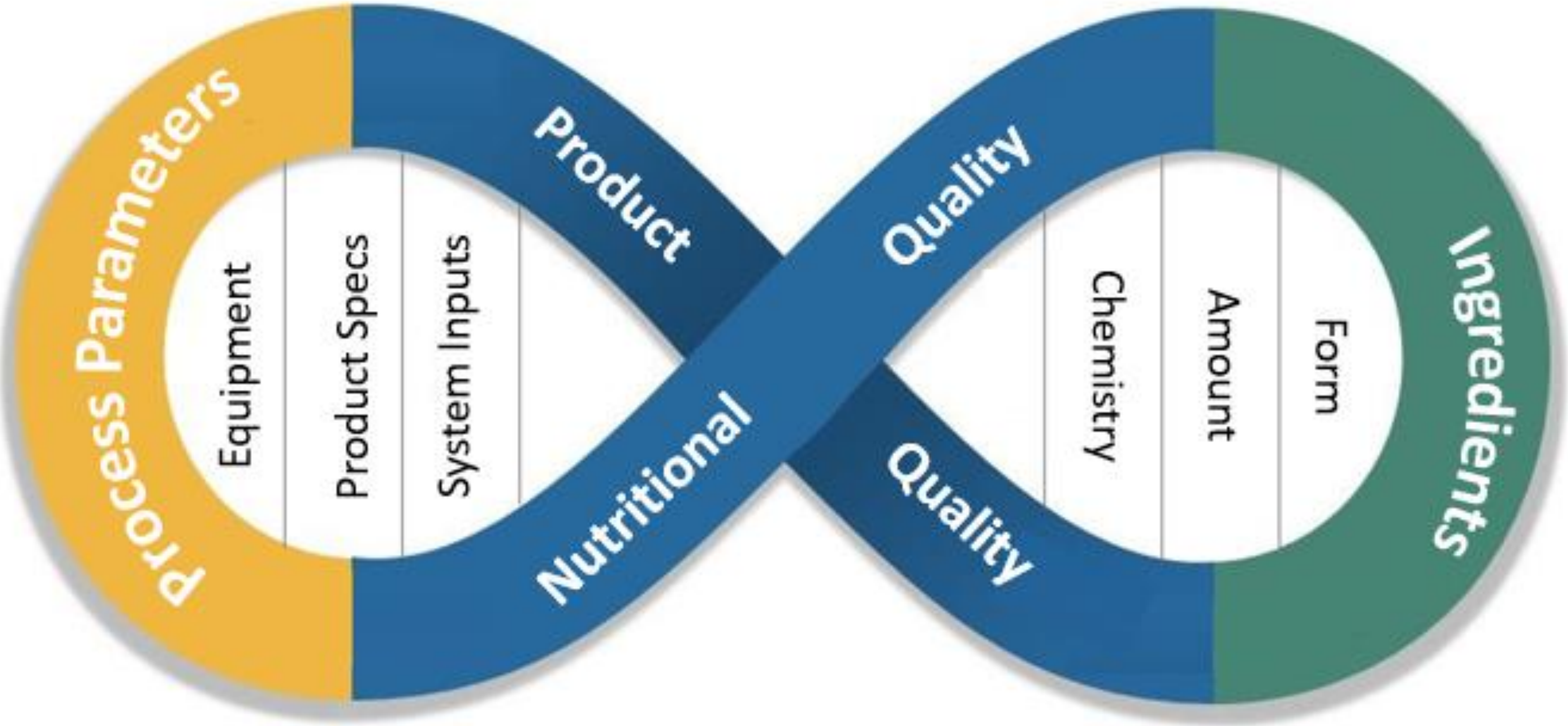
Generally:

- Larger starch granule sizes (leads to greater degree of swelling)
- Higher amylopectin content (i.e. waxy starches increase viscosity)
- Degree of gelatinzation (i.e. higher gelatinzation rates)
- Starch content of the matrix (i.e. higher starch increases viscosity)

Cereal Flour	Pasting Viscosity
Corn	1,868 cP
Barley	2,308 cP
Oat	2,456 cP
Wheat	2,746 cP

REFERENCE:
Effects of Moisture Content on Physical Properties of Extruded Cereal Flours
Available from: https://www.researchgate.net/figure/Paste-viscosity-of-cereal-flour-and-extruded-cereal-flour-at-different-moisture-content_tbl1_263997326

Session Summary
processing & Ingredients are interrelated



Question & Answer Session

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