Food extrusion. Traditional and new trends

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Sustainability in the XXI\textsuperscript{th} Century

The IPAT Equation

\[ I = P \cdot A \cdot T \]

\( I \): Environmental Impact (e.g. resource depletion, waste accumulation)
\( P \): Population
\( A \): Affluence (Average amount of technology units per person)
\( T \): Technology, or the amount of environmental impact per unit of technology
The “Weighed” IPAT Equation

\[ I = \sum_{i=1}^{i=3} (P.A.T)_i \]

\( i = 1 \) Highly Industrialized Countries
\( i = 2 \) Nations in Rapid Development
\( i = 3 \) Poor Nations

Importance of sustainable technologies

Sustainability in the XXI\textsuperscript{th} Century

Is extrusion processing a sustainable technology?

Is extrusion processing a sustainable technology?

**People/Social Dimension**
- Provide the needs of the poor?
- Extrusion accessible to all level of technical education
- Social Acceptance?
- Safety, smell, occupational health? Positive impacts
- Noise? Within legal limits

**Planet/Ecological Dimension**
- Depletion of abiotic resources? Positive impact
- Depletion of biotic resources? Positive impact
- Global warming; photochemical ozone pollutants? Positive Impact
- Acidification and thermal pollution? Positive impact

**Profit/economic dimension**
- Non-renewable resource depletion? Fossil fuel depletion? Positive impact
- Drinking water depletion? Positive impact
- External costs for concerns to the ecosystem? No concerns identified
- Capital or operational expenditures? Positive impact
Decision-making graph for sustainability-driven technology development

- **Emerging sustainable processing technology**
- **Mature sustainable processing technology**
- **Condemned processing technology**
- **Threatened processing technology**

**Axes:**
- **Technology Sustainability**
- **Market Attractiveness**
Process Intensification Concept

“Novel equipment, processing techniques, and process development methods that, compared to conventional ones, offer substantial improvements in (bio)chemical manufacturing and processing”.

Is extrusion processing a sustainable technology?

PROCESS PARAMETERS
- Associated to Raw Material
  - Composition: Oil, starch, protein, fiber
  - Moisture
  - Particle Size
  - Additives

- Feed Rate
- Water Addition
- Screw Speed
- Screw Profile
- Cutter Speed
- Barrel temperature

SYSTEM PARAMETERS
- SME
- Residence Time
- Thermal Energy
- Product Temperature
- Product Pressure
- Melt Viscosity

SYSTEM DISTURBANCES
- Screw Wear
- Ambient Conditions

PROCESS PARAMETER
- Die Profile
  - Open Area
  - Flow Resistance

PRODUCT PARAMETERS
- Product Moisture
- Product Temperature
- Bulk Density or Expansion
- Morphology
  - Shape
  - Size
  - Uniformity
- Texture/Sensory
- WSI/WAI
  - WSI: Water Solubility Index
  - WAI: Water Absorption Index
  - Gelatinisation
  - Dextrinisation

SME: Specific Mechanical Energy
WAI: Water Absorption Index
WSI: Water Solubility
GELATINISATION
DEXTRINISATION (Molecular Degradation)
EXTRUSION PROCESSING ADVANTAGES

- Lost Cost
- Large Product Range
- Energy Efficient
- No Effluents

Unit Operations
- Feeding
- Conveying
- Mixing
- Shearing
- Cooking
- Forming
- Drying and Cooling

Residence Time
10 seconds – 1min

Raw Cereal and other Ingredients

Screw pumps the material inside the barrel

Forming and expansion

Cooking by Electrical, Steam jacketed, Induction “magnetic” heating

Water Evaporation
GLASS TRANSITION

GLASSY STATE

RUBBERY STATE

Increasing temperature

Glass Transition Region

Increasing moisture

MATERIAL TRANSFORMATION CONCEPT

Glass transition temperature °C

Moisture Content (%)
TRANSFORMATIONS OF RAW MATERIALS DURING EXTRUSION

- **LIQUID (AMORPHOUS)**
  - Flashing off moisture
  - Glass transition temperature

- **Expansion**
  - Heating

- **Cooling**
  - Dry material
  - Wetting and mixing

- **GLASS**

TEMPERATURE

MOISTURE
DESIGN OF A MULTIPURPOSE SMALL EXTRUDER

Initial Motivation

• Mission to Mars
• 6-8 months outbound
• 600 days surface stay
• 6-8 months return

Lift cost to Mars:
~$200,000/kg

Actual Use

• Small (Farm) Scale Inexpensive Extruders (and Screw Press) in underdeveloped countries
Design a multipurpose small and inexpensive extruder/expeller

First Extrusion
- Soybeans
  - Extrusion
  - Pressing
    - Meal
  - Drying
    - Oil
  - Grinding
    - Soy flour

Second Extrusion
- Soy flour
  - Extrusion
  - Drying
    - Texturized soy protein
LARGE SCALE “MODEL” EXTRUDER

Triple F - Model RC 2000
Design a multipurpose small extruder

Modeling an Extrusion Process

Momentum Transfer
\[ \nabla \cdot \mathbf{u} = 0 \]
\[ \nabla \cdot \tau - \nabla p = 0 \]

Energy Transfer
\[ \rho C_p \mathbf{u} \cdot \frac{dT}{dt} = \nabla \cdot (\lambda \nabla T) + \tau : \nabla \mathbf{u} \]
Rheological Model For Soy Flour

\[ \log \eta = -0.70 \log (a^0.852_M \cdot a^1.373_T \cdot a^0.373_o \cdot \dot{\gamma}) + 5.7 \]

\[
\begin{align*}
\log a_M &= 12.55(M + b) - 2.13 \\
b &= -0.00034 \cdot T + 0.0223 \\
\log a_T &= 0.020 T - 1.23 \\
\log a_o &= 9.3 (Oil \ Content + A) - 0.088 \\
A &= -0.001347 T + 0.06866
\end{align*}
\]
Experimental validation Large Scale Extruder

Extruder geometry:
$D_b=138.94$ mm, $L=934$ mm, $H=17.08$ mm, $\theta = 6.9^\circ$

Operating conditions:
$N = 620$ rpm

Mass flow rate:
$M = 184.8$ g/sec

Material: Soy flour
## Final performance comparison

<table>
<thead>
<tr>
<th></th>
<th>Temperature rise (°C)</th>
<th>Die pressure (bar)</th>
<th>Power consumption (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Industrial Extruder</strong></td>
<td>97.8</td>
<td>19.7</td>
<td>57.4</td>
</tr>
<tr>
<td><strong>Model Prediction</strong></td>
<td>96</td>
<td>17.5</td>
<td>58.9</td>
</tr>
</tbody>
</table>

## Extrusion temperature validation

![Extrusion temperature validation graph](image_url)
Design of the Small (60 lb/h) extruder
The Extrusion-Porosification Technology is aimed to:

- Create porous powders with better rehydration time
- Reduce conversion costs (energy, capital)
- Overcome some limitations of spray drying & drum drying technologies
- Process complete formulations without further mixing
- Leverage in-built extrusion flexibility
Typical Skim Milk Powder Process

% Solids  12  → 50  → 93  → 96
Effect of solid content in the feed on the energy consumption for the evaporation of water in the spray drying process.

<table>
<thead>
<tr>
<th>Solids in the feed (%)</th>
<th>Energy consumption (kJ/kg powder)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>24,000</td>
</tr>
<tr>
<td>20</td>
<td>10,500</td>
</tr>
<tr>
<td>30</td>
<td>6,200</td>
</tr>
<tr>
<td>40</td>
<td>4,000</td>
</tr>
<tr>
<td>50</td>
<td>2,700</td>
</tr>
</tbody>
</table>
EXTRUSION-POROSIFICATION TECHNOLOGY

VISCOSITY OF PROTEINS AND OTHER MACROMOLECULES

Limitations of spray drying

Viscosity

Brookfield Viscosity at 25°C

Newtonian Behavior

Time-independent non-Newtonian behavior

Whey Protein

Skim milk

Whey Protein Concentrate

Maximum concentration permissible for spray drying

Solids Concentration (%)

Solids Concentration (%)
Simplified flowsheet for the extrusion-porosified milk powder manufacturing process
Extrusion-textured foam obtained from 38% dry solids milk protein concentrate

Energy Analysis

Typical SEM picture of an extrusion-porosified milk powder particle

Bouvier and Campanella (2013). Extrusion Processing Technology. J. Wiley (In press) - (courtesy of CLEXTRAL, France)
## Characteristics of extrusion-porosified whole milk powder

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Extrusion-porosified powder</th>
<th>Standard values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture (%)</td>
<td>2.5 – 3.9</td>
<td>&lt; 4</td>
</tr>
<tr>
<td>Fat (%)</td>
<td>27 – 28</td>
<td>27 – 29</td>
</tr>
<tr>
<td>Insolubility Index (mL)</td>
<td>0.1 – 0.2</td>
<td>&lt; 0.5</td>
</tr>
<tr>
<td>Titratable acidity (%)</td>
<td>0.1</td>
<td>&lt; 0.15</td>
</tr>
<tr>
<td>Flavour &amp; Odour</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Appearance &amp; Colour</td>
<td>Normal</td>
<td>Normal</td>
</tr>
<tr>
<td>pH (10% solution)</td>
<td>6.73 – 6.77</td>
<td>&gt; 6.6</td>
</tr>
<tr>
<td>Free fat (%)</td>
<td>3.2 – 6.7</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>Peroxide value (meq. O₂/kg fat)</td>
<td>0.3</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Water activity</td>
<td>0.22 – 0.27</td>
<td>&lt; 0.5</td>
</tr>
<tr>
<td>Density (kg/L)</td>
<td>0.41 – 0.44</td>
<td>&gt; 0.4</td>
</tr>
</tbody>
</table>

Bouvier and Campanella (2013). Extrusion Processing Technology. J. Wiley (In press) - (courtesy of CLEXTRAL, France)
**Reactive Extrusion**

**Research/Development Output**

- Graph showing the number of reactive extrusion publications over years from 1986 to 2010.

**Green Chemistry**

**Raw Materials**
- Plant Proteins
- Animal Proteins
- Plant Proteins
- Cereals
- Starches
- Wood
- Oilseeds

**Molecules**
- Alcohol/solvents
- Chemicals
- Oil and Lubricants
- Surfactants
- Chemicals
- Paper

**Process Comparison**

**Sodium Caseinate**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Reactive Extrusion</th>
<th>Traditional Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Content (%)</td>
<td>16-28</td>
<td>70-80</td>
</tr>
<tr>
<td>Temperature, °C</td>
<td>120-140</td>
<td>70-80</td>
</tr>
<tr>
<td>Time</td>
<td>15-20 sec</td>
<td>30-45 min</td>
</tr>
<tr>
<td>Energy Cost</td>
<td>60 -70</td>
<td>100</td>
</tr>
<tr>
<td>Capital Cost</td>
<td>~ 50</td>
<td>100</td>
</tr>
</tbody>
</table>

**Concept**

- Use the micromixing capabilities of twin-screw extruders along chemical reactions.

**Diagram**

- Feed section
- Bulk reaction section
- Vventing section
- Bulk reaction section
- Vventing section
- Formulation section
- Pumping/Cooling section

Neutralization Reactions

“Batch” Production of Sodium caseinate

- Wet acid casein + water
- Grinding
- Dissolution and Neutralization
- Drying
- Grinding

Caseinate powder

Extrusion Process

- Casein/water mixture
- Extruder
- Exchanger (Sodium Hydroxide)
- Roller Dryer

Caseinate powder

- Casein can be fed dry or wet
- 10-30% moisture content after alkali is added
- Functional properties are different (e.g. emulsification)
- Higher solid contents are handled
- Less labor and floor space
Production of Sodium Caseinate

Bouvier and Campanella (2013). Extrusion Processing Technology. J. Wiley (In press) - (courtesy of CLEXTRAL, France)
Concept – Use the micromixing capabilities of twin-screw extruders along chemical reactions

Some Twin screw geometries

Rectangular Channel Model

Cross-channel section – velocity profile

Down-channel section – velocity profile

Mixing and Deformation of material

**Reactive Extrusion**

**Single screw** extruder as a bioreactor for sago starch hydrolysis

Starch + enzyme → 60-120°C

\( \alpha - amylase \)

**Conditions**
- Feed Moisture
- Enzyme concentration
- Mass Temperature

**Extrusion**

**Results**
- Water Solubility Index (WSI)
- Water Absorption Index (WAI)
- Degree of Gelatinization (DGR)
- Dextrose Equivalent (DE)

Influence of feed moisture and enzyme concentration on DE of sago starch extrudates produced in a single screw extruder

High moisture twin screw extrusion of sago starch. Saccharification

**Reactive Extrusion-Reactor Approach**

- **Starch** → **Twin Screw Extruder** → **Batch Reactor**
- **α-amylase**
- **Rx time 30-40 secs**
- **Amyloglucosidase**
- **Rx times 8hrs**
- **Product**
  - DE
  - WSI (Water Solubility Index)
  - % Saccharification

**Reactive Extrusion Approach**

- **Starch** → **Twin Screw Extruder**
- **α-amylase**
- **Rx time 30-40 secs**
- **Amyloglucosidase**
- **Product**
  - DE
  - WSI (Water Solubility Index)
  - % Saccharification
Influence of enzyme concentration and barrel temperature on DE of extrudate produced by twin screw extrusion at 39.5% moisture content at 130rpm

Effect of enzyme concentration (AMG), moisture content and stage of addition of the enzyme in a twin screw extruder on WSI
SUMMARY

The examples described shows that Extrusion Technology can be considered a Process Intensification technology getting more interest particularly due to more incentives for the development of sustainable technologies.

- **Process intensification/Extrusion** can promote continuous processing instead of batch, or semi-batch processing. Higher throughputs with equivalent or even smaller volume devices result from continuous processing, hence leading to higher process productivity, smaller plants, safer processing, and reduced capital and operating costs.
- **Process Intensification/Extrusion** develops and promotes multifunctional processing equipment
- **Process Intensification/Extrusion** accelerates fundamental process phenomena such as physical transfer phenomena and chemical reactions.
GRACIAS POR SU ATENCION