2015 marks 100 years of AACC International members working together to share cereal grain science. The Centennial Committee, with the help of many expert members, is creating activities to celebrate achievements and look to the future of our science. The Scientific Milestones Sub-committee is coordinating a series of summary highlights—each focusing on an important area of cereal grain science. Experts in each area have identified key breakthroughs over the last 100 years, provided brief descriptions of the discoveries, and given examples of how these breakthroughs led to changes in our cereal foods. The experts also provide a few ideas on where future research may lead us. These brief highlights are meant to provide an overview and cannot be inclusive of the exhaustive research in these areas.

Centennial Scientific Milestones Sub-committee: Lauren Brewer, Rachel Prososki, and Steven Nelson.

Raising the Profile of Food Processing[1]

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Introduction

Cereal crops and their cultivation have played a critical role in the evolution of human civilization from a nomadic and hunter gatherer way of life into a community based one. The conversion of cereal crops into important ingredients has been instrumental in development of the current state of our civilization—the advent of rural and urban communities and significant population growth worldwide.

Cereals belong to the monocotyledonous family of grasses called Gramineae and include wheat, maize, oats, rye, rice, triticale, millet, sorghum, and barley. Food products derived from cereal kernels or seeds play a significant role in meeting the energy and macronutrient needs of humans. Conversely, cereal processing plays a significant role in converting raw cereal kernels into ingredients that can meet these energy and nutrient needs. Of all the different types of food products we consume today, cereal-based foods provide about 70% of calories and 50% of proteins. They are also a significant source of micronutrients in the human diet: 20% of magnesium and zinc, 20–30% of riboflavin and niacin, and 40% of thiamine (1) are obtained from cereal-based products. The importance of cereal foods can be inferred from the fact that cereal production per capita has increased from about 280 kg in the first half of the 20th century to about 340 kg in the early 21st century (1). This increase in cereal production, accompanied by a significant increase in worldwide human population from 1.6 billion in the early 1900s to 5.3 billion by the 1990s, underscores the role played by cereal processing in the current state of human civilization.

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Cereal Processing Technologies

Various processing technologies used to convert cereal kernels into foods that consumers are familiar with are illustrated in Figure 1 (provided at end of article). These processes include the following.

1. Drying technologies for safe storage of cereals
Cereal kernels mature at high moisture content (20–30%) depending on type, and safe and prolonged storage of cereals without leading to spoilage is facilitated by drying technologies. Drying processes may include spreading the kernels and naturally drying them under the sun or may involve large-scale industrial dryers and the application of controlled heat and air flow to bring the moisture content to <14.5%.

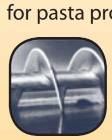
2. Milling and fractionation technologies
Milling and fractionation are ancient technologies. Hand milling of cereals with mortar and pestle, one of the earliest

1900s World population at 1.6 billion

1901 Introduction of Beall Degerminator in maize dry-milling operations

1930s Development of continuous extrusion and automated processes for pasta production

1940s Further development of continuous extrusion and automated processes for pasta production



1957 Instant ramen-style noodles developed in Japan

milling technologies, dates back to prehistoric times, while methods for separating starchy "milk" from gluten and other fractions in wheat were developed around 200 BC. Current milling technologies can trace their origins to the 1870s and 1890s when roller mills and gradual reduction systems were first developed. The Beall Degerminator was introduced in maize dry-milling operations in the early 1990s.

Milling technologies can be classified into two types: dry and wet. Dry milling separates various botanical parts of the kernel—separation of endosperm from the pericarp and embryo or germ—and is also used to reduce the particle size of endosperm into flour or grits. Wet milling is used to separate starch from protein in cereal kernels especially wheat and maize.

3. Bread production technology

Processing of cereals into flours has led to development of many familiar foods, including breads. Bread baking technologies played an important role in the evolution of breadmaking from home kitchens to the current large-scale operations that make this product widely available at an affordable cost to consumers while retaining significant amounts of macro- and micro-nutrients. Breads are produced from mainly three types of baking processes:

a) Dough development by bulk fermentation process: Examples include traditional straight dough or sponge and dough processes.
b) Dough development by mechanical means: Examples include the Amflow or Chorleywood bread process (CBP) introduced in the 1960s.
c) Dough development by oxidizing and reducing agents: Example includes activated dough development (ADD) introduced in the 1960s.

4. Malting, brewing, and distilling

Brewing and distilling have been practiced for centuries to produce fermented beverages. Cereal kernels are the starting material for the production of beers and liquors. The process starts with use of endogenous enzymes in cereals to produce malts, followed by brewing through yeast fermentation and subsequent distillation to produce potable spirits, including whisky. Barley is the most commonly used starting material for brewed and distilled alcoholic products; however, other grains, including sorghum, millet, rice, maize, and wheat, are also used. Advances in the science of brewing and process technologies have resulted in production of beers or potable spirits with unique and consistent flavor profiles with every production lot.

5. Extrusion processing technology

Food extrusion is a process in which various ingredients in appropriate particle sizes are transformed into a final or intermediate food product through application of mixing, shearing, and/or thermal energies. Cooking extrusion processes are characterized by short extruder dwell times, typically <1 min. Extruder devices with single or twin screws are used to produce diverse products, including direct expanded snacks and ready-to-eat (RTE) breakfast cereals, pet and aquatic foods, stabilized rice bran, pasta, noodle products, and others. The development in the 1990s of novel supercritical fluid extrusion for food applications expanded potential applications even further.

6. Pasta processing and other whole grain products

Pasta Processing. Pasta products are an important component of the human diet in many regions of the world today, and archaeological evidence points to the consumption of these products in Italy as early as 600 BC (2). A wooden extrusion press for making pasta products was developed in the 1700s. However, continuous extrusion and automated processes for pasta production developed in the 1930s and 1940s contributed to current widespread consumption and availability of different types of pasta products.

Traditionally, pasta products were prepared from durum wheat dough in an uncooked state. As a better understanding of chemistry and the science of pasta quality was developed, ingredient and process technologies were employed to deliver attributes important to pasta quality. Examples include controlled particle size distribution in semolina flours used to make pasta products, development of drying processes to 1) optimize protein denaturation and prevent starch leaching during cooking; and 2) develop safe products without harmful microorganisms.

Rice Substitutes Including Bulgur Wheat. Bulgur wheat production technologies have evolved from a handmade process called *arisah* in the Old Testament of the *Bible* to

1960s
Development of CBP & ADD bread-baking processes and introduction of single-screw extrusion processes for RTE breakfast cereals

Late 1960s
Green revolution leading to increased agricultural production

1990s
Development of novel supercritical fluid extrusion for food applications

1990
Formation of the AACCI Engineering & Processing Division

World population at 5.3 billion

current continuous processes. During soaking and steaming operations in the manufacturing process, important micronutrients, including vitamins and minerals, move from the outer portions of the kernel into the endosperm fractions. Thus, partial removal of the outer layers of wheat does not completely reduce the nutritive value of the product. Larger scales of operation for producing bulgur products have enabled their inclusion in food aid programs for some countries as low-cost rice substitutes.

7. Breakfast cereal products

Western consumers are very familiar with breakfast food products, including crisp rice puffs, corn flakes, and oatmeal. The first RTE breakfast cereal is believed to have been introduced in 1863 in the United States (2), while the first patent for flaked cereals was applied for in 1895 by John Harvey Kellogg. Cereal process technologies play an important role in converting cereal kernels into desirable products that have become the staple of many breakfast diets. Examples include the following.

a) Oatmeal products: Using oat cereal as a starting material, the processes of cutting, steaming, and flaking are applied to produce oatmeal breakfast products. Depending on the process parameters used in these operations, oatmeal products that require significant cooking or instant porridges can be produced.

b) Cereal flakes from extrusion process: While cereal flakes can be made from a pressure cooking process followed by flaking and drying, continuous extrusion processes used to cook the cereals have increased in popularity since the introduction of single-screw extrusion processes for RTE breakfast cereals in the 1960s. A single- or twin-screw cooking extruder is used to plasticize the starch in the cereal along with other flavoring ingredients. The presence of water and heat along with shear stresses in the extruder leads to starch gelatinization and protein denaturation. The intermediate product from a cooking extruder is subsequently formed into desirable shapes using a forming extruder, followed by flaking, toasting, or drying into the final product.

c) Oven puffing and gun puffing: Crisp puffed rice used in RTE breakfast products is familiar to many and is an example of rice cereal that is oven puffed (2). The oven puffing process employs heat (e.g., in an oven) to convert cooked and shaped cereal products (e.g., bumped rice) into expanded and puffed crispy products. In the gun puffing process, cereals like native rice or extruder cooked cereal intermediates at an appropriate moisture content is introduced into a chamber and subjected to high pressure and temperature. Starch is converted into a plasticized state, and the subsequent release of pressure expands the water in the cereal into a vapor phase that increases the volume of the cereal several-fold. The cereal product is "shot" out of the chamber when the pressure is released.

8. Alkaline maize nixtamalization

The production of corn tortillas and corn tortilla-based snacks involves an ancient process called nixtamalization. This process is believed to have led to the development of Meso American civilizations, as it enabled these communities to depend on a single cultivated crop. This was mainly due to the improved bioavailability of two essential amino acids—lysine and tryptophan—that results from the nixtamalization process. Nixtamalization involves cooking maize kernels in the presence of lime (calcium hydroxide) and water, followed by steeping of this liquor, subsequent grinding of the steeped and washed kernels (nixtamal) into masa (dough), and transformation of the masa into soft tortillas or crispy tortilla chip products. Larger scale nixtamalization processes have made these types of nixtamalized products available to consumers. This process also results in improved bioavailability of certain nutrients, including niacin, calcium, and proteins, and reduces the potency of anti-nutritional factors like phytic acid and mycotoxins (3).

Significant Advances in Cereal Processing Technologies

1. Post-harvest drying technologies

Post-harvest drying technologies are employed to reduce the moisture of cereal crops to <14.5% to prevent microbial spoilage or sprouting during storage until they are ready to be utilized. Cross-flow, co-current, and counter-current air-drying processes are typically employed in the cereal drying industry (4). Cereal kernels, including wheat, maize, and rice, are sensitive to temperatures and dwell times employed in the drying process. For example, a drying temperature that is too high causes rapid moisture gradients inside the kernel that lead to development of stress cracks and subsequent loss of yield in further processing that translates into a higher cost of ingredient or product for consumers. Similarly, drying conditions should also not be so severe as to affect the functionality of certain fractions in the cereal (e.g., gluten protein in wheat).

In recent years, there has been an interest in employing new technologies for cereal drying. This has been driven mainly by throughput, energy, and quality considerations. New technologies include the following.

a) Rotated jet spouting bed drying (5): This technology employs circulation of hot air in a rotating chamber and has been studied for slow drying cereal kernels like corn. Intermittent drying along with significant tempering periods to allow moisture migration to the surface results in dried corn with fewer stress cracks. The process has been found to be significantly more energy efficient than standard drying technologies.

b) Solar assisted drying: In developing countries with tropical climates and an abundance of solar energy, this type of drying plays an important role in ensuring economic viability and food security for communities. The principles employed in this technology are very simple: a solar "collector" consisting of a matt-black substance covered by a transparent UV-stabilized plastic and natural or forced convection to transfer hot air from the collector to a bed of cereals. The collector can use locally available materials, including burnt husks, charcoal, black-painted metal chips, black rock pebbles, black colored plastic, etc. Examples of these dryers include Asian Institute of Technology (AIT) dryers in South East Asia and Hohenheim-type solar tunnel dryers used in more than 35 countries (5).

2. Milling and fractionation technologies

The flour milling industry operates on small margins and many of the advances include improving efficiencies in existing equipment. Some of the significant breakthroughs that have happened in the last 50 years include the following.

a) Reduction in amount of grinding equipment used to process a given amount of wheat in a given period of time: For example, in the break system the available roll surface, expressed in mm per 100 kg of wheat processed per 24 hr, has more than halved from a starting value of 18 mm/ 100 kg/24 hr (4).
b) Reduction in sifting and conveying requirements through development of double roller mills: This has enabled materials to be ground twice, eliminating the need for some sieving requirements.
c) Pin mills: When endosperm flakes are produced during the reduction steps, these flakes are broken up into flour-size particles through centrifugal forces without significant additional starch damage. This has reduced the number of roll mills required to produce flour products.
d) Debranning of wheat: Debranning technologies employed in rice and barley milling were adapted to wheat, enabling significant improvements in extraction and flour quality. In the wheat debranning process, conditioning time is reduced to minimize water penetration into the endosperm (6). Subsequently, kernel-to-kernel friction and kernel-to-surface abrasion passages in a debranning machine peels off the wheat bran, leaving the aleurone layer with the endosperm fraction. The debranned material then goes into the standard milling process. In addition to capacity increases, wheat debranning also results in flours that impart better properties to baked products, including higher loaf volume and improved nutrition due to inclusion of the aleurone fraction in the flour.

β-Glucan, a non-starch polysaccharide is a soluble dietary fiber that is present at commercially significant levels in barley and oats. β-glucans when present at physiologically effective concentrations have been associated with reduced risks of chronic health problems, including cardiovascular diseases and diabetes. Thus, there is a need to increase the consumption of β-glucans in the diet, and several interesting technologies have been developed to produce barley and oat ingredients enriched with β-glucan fractions for application in foods and beverages (7). An overview of wet and dry fractionation technologies is presented in Figure 2 (provided at end of article). It is important to understand the impact of these process technologies on the physiochemical properties of β-glucans that contribute to the health benefit of these ingredients.

3. Extrusion processing

Improvements in several elements of extrusion processing have contributed to its versatility and application in diverse food products. Some of these improvements include (8):

a) Segmented or modular barrel and screw designs to enable production of different types of products on the same extruder by changing screw profiles.
b) Grooves in the barrel to move the material forward and prevent product from turning with the screw. Alternatively interrupted flights and shearing bolts can also prevent the product from turning with the screw.
c) Use of shear-locks or steam-locks that allow each section in a given extruder to function as a "pressurized reactor" where mixing, shearing, and thermal-driven material changes can occur.
d) Steam preconditioning of starting material in "dry" type extrusion processes where product heating is accomplished only by mechanical friction in the extruder. The preconditioning aids in hydration of ingredients and reduces wearing of screws and barrel significantly.
e) Adaptation of twin-screw extrusion from the plastics industry in the mid-1980s. Twin-screw extrusion provides more flexibility in certain operations, including those that require frequent product changeovers, <1.5 mm product sizes, ability to handle higher fat-containing formulations (18–22%), and capability to process raw materials that have fine particle size distributions.
f) Development of gravimetric or loss-in-weight raw material feeders have contributed to less variability in key extruder process parameters, including melt moisture, degree of fill, and die pressures. This has resulted in consistent bulk density and texture of finished products.
g) Development of novel in-line sensors that can display deviations in desired product characteristics. Examples of these sensors include acoustic tools to measure the properties of "popping" sound during product expansion at die exit and near infrared (NIR) absorbance of the melt to characterize material transformations in the extruder (9,10).

4. Bread baking technology

Development of dough preparation technologies followed different paths in the United States and Europe. In the United States, application of continuous dough technologies, including the Do-maker and Amflow process, peaked in the 1970s followed by a switch to bulk fermentation methods such as the sponge and dough method that is currently popular in U.S. pan bread operations (11). In the United Kingdom the continuous CBP process is still widely used for pan bread operations. The Do-maker and Amflow process employs a liquid ferment process, followed by initial dough preparation and intensive high-speed mixing of the dough at pressure. These processes also result in bread crumb cell structures that are unoriented, leading to a gummy texture upon mastication. CBP does not require liquid ferment systems, and dough development is achieved by high-speed mixing (e.g., Tweedy mixer) in which the mixing energy is about 5–8 times that of mixing employed in the traditional sponge and dough process. A comparison of sponge-dough, Amflow and Do-maker, and CBP processes is illustrated in Figure 3 (provided at end of article) (11,12).

With the introduction and subsequent popularity of bakeries in large retail grocery stores, freezing technologies began to be used to make various types of bakery products in these locations (13). Applications of freezing technology in the production of bakery products include 1) unproofed frozen dough systems that require final thawing and proofing before baking (e.g., croissants and variety breads); 2) pre-fermented frozen dough systems for ready-to-bake products (e.g., croissants, ciabattas, and seeded bread rounds); and 3) par-baked bread technology with pre-baking and freezing followed by final baking at the sell-off point. Pre-baking is done at lower oven temperatures with steam, and the final bake-off creates the crust and flavor in the sold product. This technology is mainly used for crusty bakery products, including baguettes and variety bread rolls.

Another interesting technology that researchers have studied is the use of supercritical fluids like CO_2 in a continuous extrusion process to produce bread-like products (14). Supercritical CO_2 is used as the leavening agent in place of yeast. Different sections of the extruder are functionally designed to mix and develop the gluten network in the dough, and supercritical fluid that may contain flavor adjuncts is injected into the extruder. The dough is subsequently directed to an outlet die to shape the products. Expansion of the dough happens due to the pressure drop occurring in the die and die exit. The expanded dough shapes are then baked to produce familiar bakery products. Although this technology has not been commercialized yet, it offers several benefits, including elimination of bulk fermentation and long proofing steps.

5. Alkaline nixtamalization of maize

The process of nixtamalization has not changed much over the centuries except in the economies of scale practiced. Figure 4 (provided at end of article) illustrates the various steps in the process, and the products from this process play a significant role in the human diet. For example, dry masa flour is used in approximately 40% of table tortillas made in Mexico, while corn and tortilla chips comprise a majority of lime-cooked corn products in the United States (3). Cooking and grinding parameters are different for different products, including table or soft tortillas and snack products like tortilla chips. A major challenge during nixtamalization is the generation of wastewater from corn cooking and steeping steps. This alkaline wastewater contains high amounts of solids lost from maize during cooking, steeping, and washing steps. Thus, recent technological changes to the process have been driven by water and environmental conservation efforts. Researchers in the last several decades have studied the use of a continuous lime extrusion process and alkaline protease or arabinoxylan enzyme treatments to reduce fresh water usage (3,15). Although these technologies have not been commercialized yet, research continues to be done to improve the quality of products made from these alternative processes.

6. Noodle processing technology

Handmade noodle technology and noodle consumption originated in China around 200 BC and was introduced in Japan about 1,200–1,800 years ago (15). Subsequently, the consumption of noodles spread to many countries in South East Asia, and the introduction of instant noodles by the Japanese in 1957 made this food popular in Europe and the United States. The importance of noodles is illustrated by the fact that 30–40% of total wheat flour consumption is through these types of products in several South East Asian countries (16). Most noodles produced today are made on machines, and the basic principles of noodle manufacture is the same, even though selection of specific process steps and formulations may depend on local consumer preferences. Various processing steps in noodle manufacturing are designed to produce noodle taste attributes that match those of handmade noodles, with varying degrees of success.

Figure 5 (provided at end of article) illustrates the common steps involved in the manufacture of different types of noodle products. As mentioned above, various technological improvements to the larger scale noodle manufacturing process attempted to match product attributes of handmade noodles. These process changes include 1) use of vacuum mixers that enable higher water absorption in dough, resulting in higher starch swelling during the steaming operation and shorter cooking time in consumers' homes; and 2) wavy sheeting rollers to aid in gluten development and achieving desired final noodle texture.

Conclusions

Processing of cereals has had a significant impact on the human diet, and products that consumers are familiar with today would not have been possible without advances in cereal processing technology. In many parts of the world, cereal processing has enhanced utilization of locally grown grains and provided consumers with access to nutritious and affordable cereal-based food products. Cereal processing has also improved food safety, as many of these processes include application of thermal energies that prevent growth of harmful microorganisms. Future advances in cereal processing will continue to focus on developing technologies to reduce energy and water usage in processes and to improve the bioavailability of various cereal grain components for health benefits.

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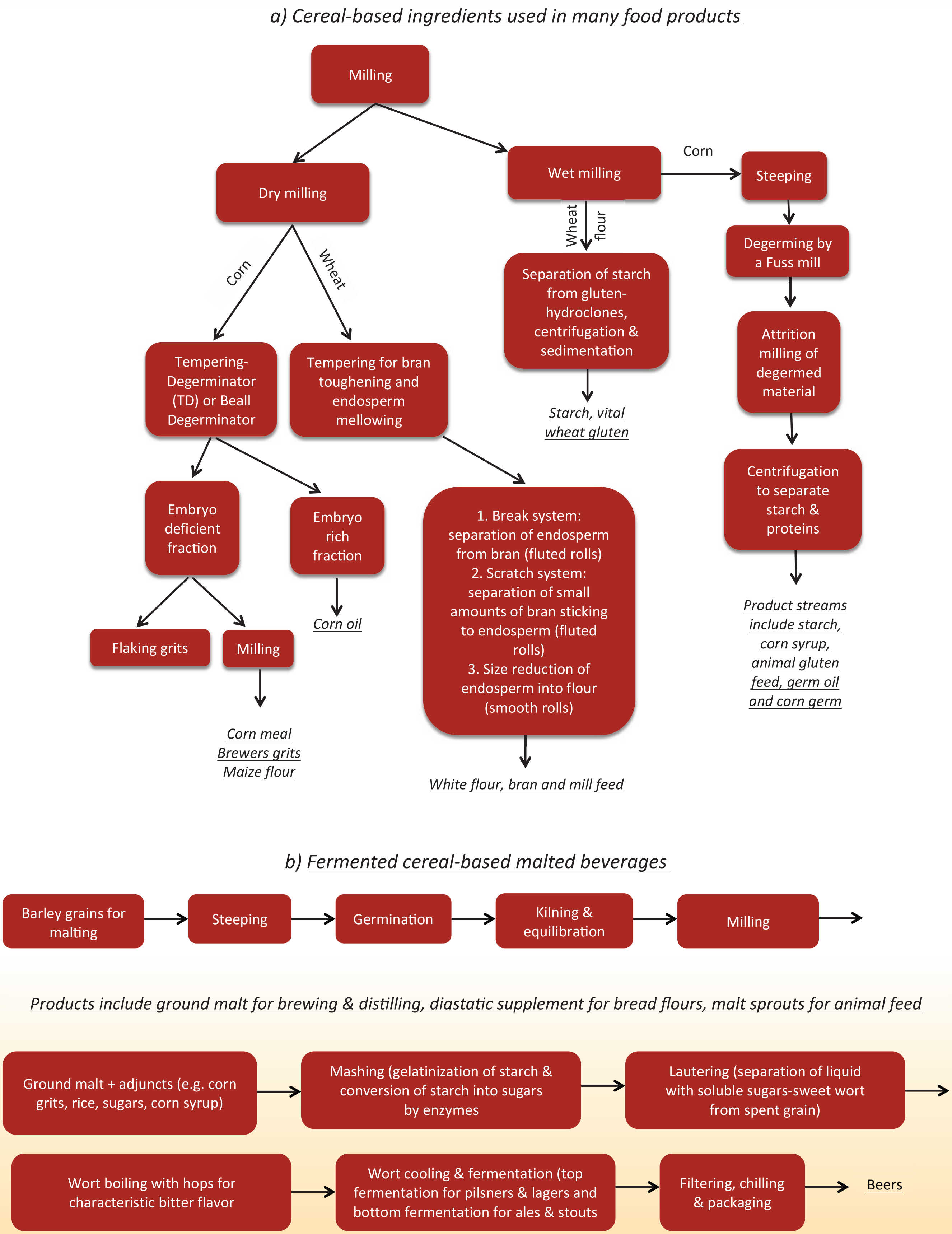

Fig. 1. Role of processing technologies in development of cereal food ingredients. **a)** Cereal-based ingredients used in many food products; **b)** fermented cereal-based malted beverages; **c)** RTE cereals and breakfast foods; **d)** puffed RTE cereals. *(Continued on next page)*

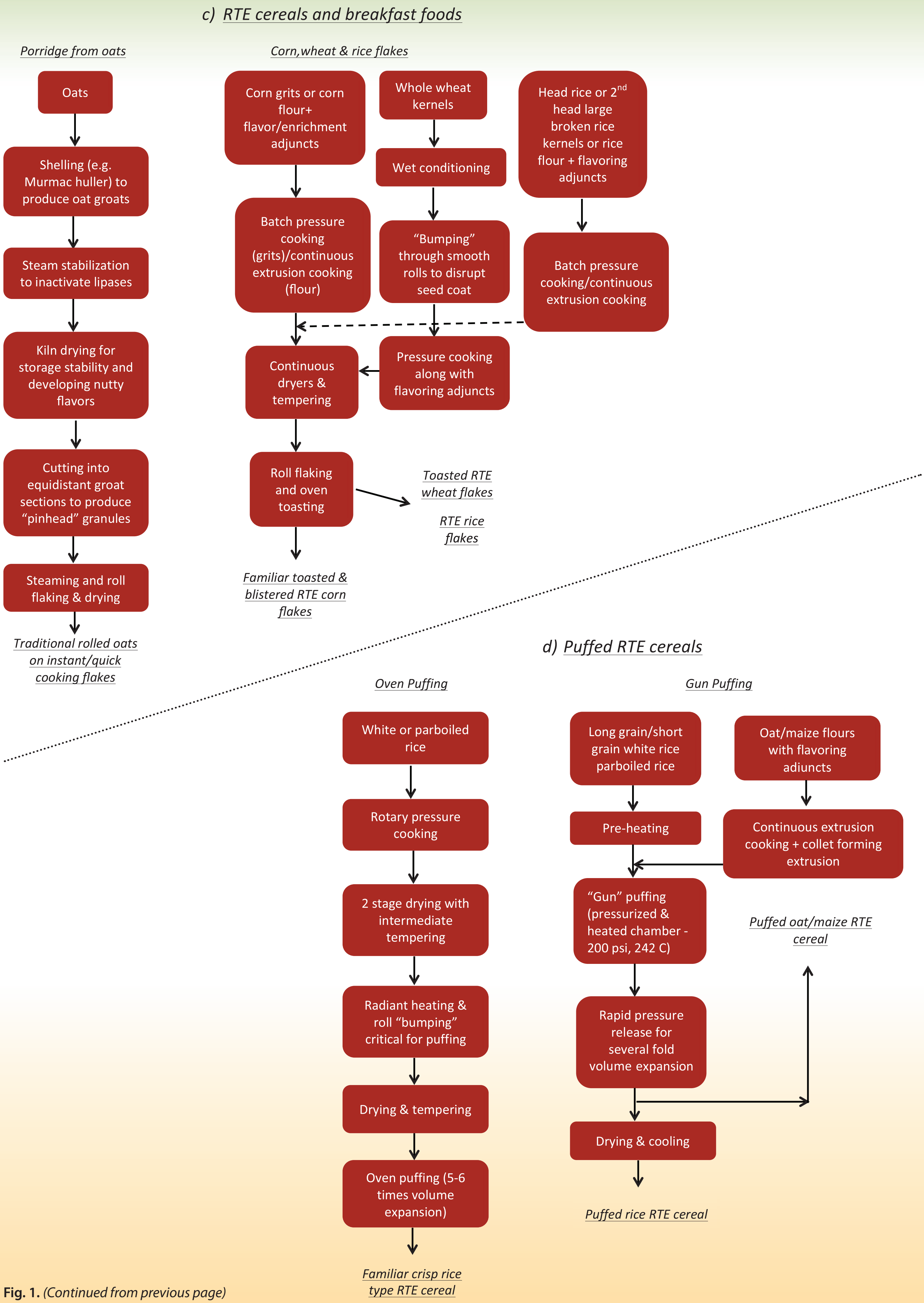

Fig. 1. *(Continued from previous page)*

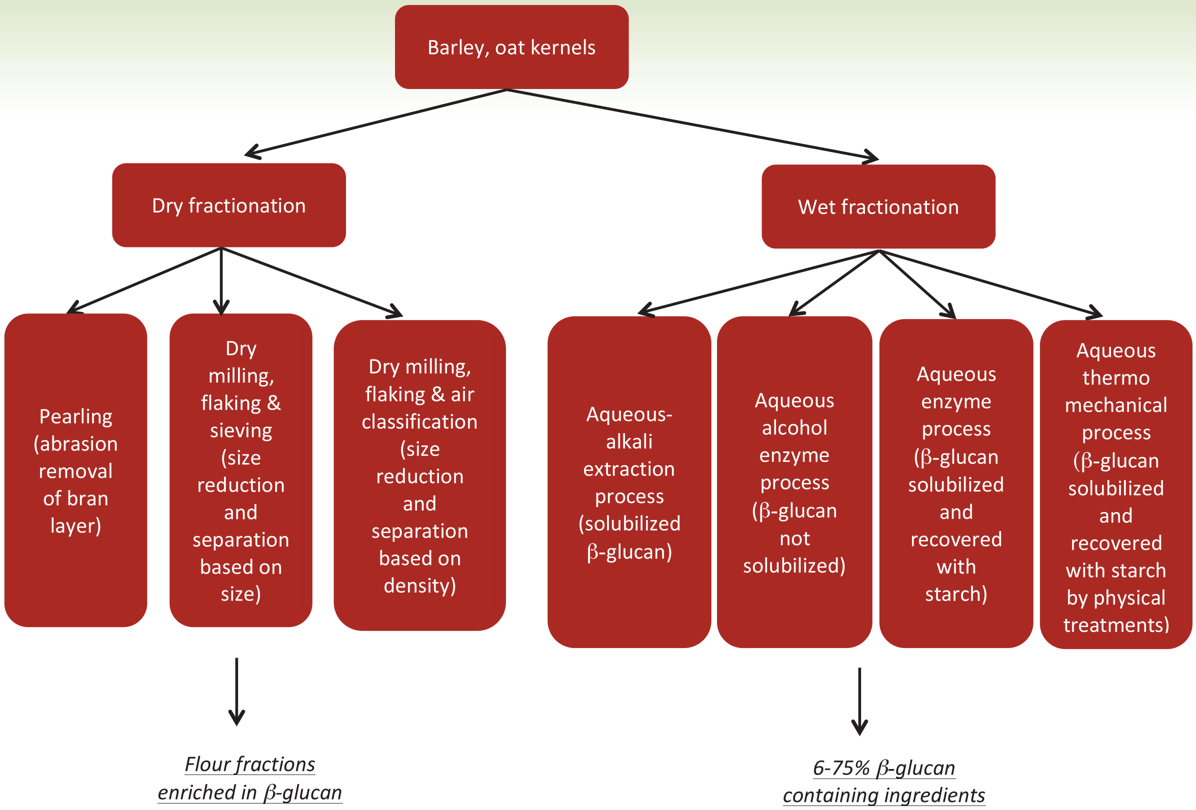

Fig. 2. Overview of dry and wet fractionation technologies used to produce β-glucan enriched cereal ingredients.

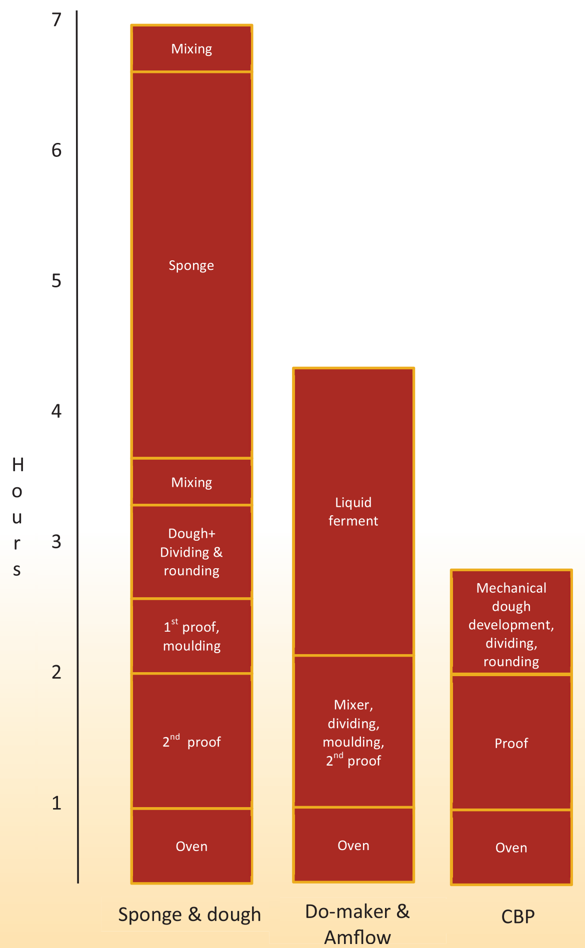

Fig. 3. Comparison of conventional and continuous breadmaking systems (12).

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Fig. 4. Steps in alkaline lime-cooking of maize (nixtamalization process).

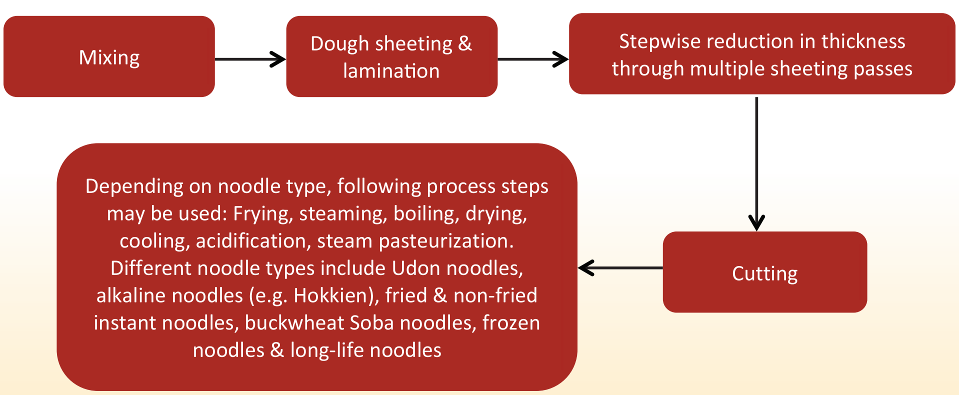

Fig. 5. Processing steps for manufacturing various types of noodles.