Sustainable Recovery and Reutilization of Cereal Processing By-Products

Edited by Charis M. Galanakis

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Preface

Cereals represent the most important source of food and feed for direct human consumption and meat production, respectively. Being an important source of a broad range of phytochemicals (e.g., carbohydrates, proteins, lipids, vitamins, inorganic, and trace elements), they are known to possess well-established beneficial effects to human health. Epidemiological studies have shown that regular consumption of whole cereal grains is associated with reduced risk of developing chronic diseases such as cardiovascular disease, some cancers, and type 2 diabetes. Cereals manufacturing includes common processes such as dry milling (wheat and rye), pearling (rice, oat, barley), wet milling (corn, wheat), and malting (barley, corn, wheat), which generate by-products that differ in their physical state and chemical composition. However, all of them contain similar beneficial compounds for human health, which could be recovered and recycled in the food chain.

The current handling of cereal processing by-products includes management practices that either degrade the substrate or lead to diminution of their pollution load without getting advance of their content in valuable ingredients. These practices cannot continue forever within the sustainability and bioeconomy framework of the modern food industry. Nowadays, the urgent need for sustainability within the food industries has turned the interest of research to investigate the handling of their by-products from another perspective, e.g., by adapting more profitable options. To this prospect, the major challenge for cereal manufacturers is to incorporate ingredients or whole processing by-products into foods and nutraceutical formulations. Subsequently, there is a need for a new reference covering the latest developments in this particular direction.

Over the last few years, the Food Waste Recovery Group (www.foodwasterecovery.group) has organized a series of actions (webinars, workshops, e-courses, etc.) and books targeting food waste recovery processing and industrial techniques, describing tools for the implementation of innovations in the food industry, exploring the effect of emerging and nonthermal technologies on nutraceuticals and functional foods development, and highlighting sustainable solutions for the management of specific food processing by-products from the olive, grape, and coffee industries. Along this line, this book indicates the alternatives for upgrading cereal processing residues and reveals the opportunities of reutilizing them in more profitable ways. It fills the existing gap of transfer knowledge between academia and industry by providing a guide for all the cereal manufacturers, engineers, professionals, and producers active in the field, trying to optimize industries' performance and reduce their environmental impact.

It covers the most recent advances (last 10 years) in the field focusing on the extraction of high added-value compounds and their reutilization into different fields of the food and nutraceuticals industries. It promotes solutions that ensure the sustainable management of cereal processing by-products, and analyzes the advantages, disadvantages, and real potentiality of relevant processes. The ultimate goal is to support the scientific community and enterprises that aspire to develop real, high-scale commercial applications.

The book consists of 11 chapters. Chapter 1 introduces the cereal production process and cereal processing by-products, e.g., different sources and ways of production. Since cereals are an important source of carbohydrates, proteins, lipids, vitamins, mainly of B-complex and vitamin E, and inorganic and trace elements, the reutilization and valorization of their by-products is a great challenge that is explored throughout the whole book. For example, corn bran is one of the best sources of ferulic acid, which is an antioxidant compound. Sorghum bran is a unique dietary source of 3-deoxyanthocyanidins, a flavonoid with strong cytotoxic activities. Wheat, oat, and rye bran contain dietary fiber such as arabinoxylans and β-glucans. These and many other added-value components in cereal processing by-products and their health benefits are critically reviewed in Chapter 2.

Distillers' dried grains with solubles is the major by-product of bioethanol and distillery plants, owning a share of the market as animal feed due to its high protein, water-soluble vitamins, and minerals content. The heterogeneous nature of this by-product predisposes its use as a starting raw material within a biomass-based biorefining strategy. Chapter 3 describes the compositional changes that this by-product undergoes during the bioethanol production process, with specific attention to nonstarch carbohydrates, proteins, and phytochemicals. Likewise, numerous valorization approaches and their intermediate derivatives are outlined and evaluated. In a similar approach, Chapter 4 provides an overview of the biorefinery for the conversion of wheat bran into bio-based products. A large number of methods and technologies have been covered, highlighting the recovery potential of sugars and other value-added products. Chapter 4 also provides an outline of the various steps involved in biochemical conversion of carbohydrates to biofuels and lignin (nature's most abundant aromatic polymer) to valuable products. In addition, the limitations of biomass development and lignocellulose deconstruction are discussed thoroughly.

Chapter 5 addresses the main strategies for the recovery of proteins from the by-products of the most commonly processed cereals: rice, corn, barley, and wheat. At the same time, based on the results of numerous scientific studies, proposals for their use are denoted. Chemical, biotechnological, and physical technologies are thoroughly discussed in spite of technical, economic, environmental, and legislative considerations. Chapter 6 focuses on the recovery of bioactive compounds from cereal by-products using particular membrane-based technologies. These physicochemical processes are widely adopted for the separation, fractionation, purification, and concentration of various industrial streams. At first, an outlook on general principles and properties of membrane operations is provided, prior to discussing the separation of functional macro- and micromolecules in food waste recovery applications. Target applications for the treatment of oat, rice, wheat, and corn by-products are analyzed and discussed, while the technological advances and improvements of membranes over conventional methodologies are denoted.

Chapter 7 explores the several by-products obtained after brewing and their potential applications in foods. In particular, barley brewing by-products offer an opportunity for cereal-based baked and extruded products with acceptable sensory and nutritional characteristics. Applications of polyphenolic extracts in healthcare and food processing are highlighted, whereas recovery strategies and different applications of brewer's spent yeast are denoted. Chapter 8 explores the occurrence and structural heterogeneity of arabinoxylans from cereals and their by-products, discussing the main extraction approaches and their influence on the recovered compounds. These non-starch polysaccharides show viscous and water retention properties, which confer on them high nutritional impact as dietary fiber with recognized health promoting effects. The structural heterogeneity, properties, and recovery of arabinoxylans are dependent on their tissue location and are strongly influenced by interactions with other cell wall components. The proposed extraction methods allow the recovery of different arabinoxylan structures, arabinooligosaccharides, and sugar monomers that could be valorized in food, health, and material fields.

Chapter 9 provides an overview of the applications of high added-value compounds that could be valorized from cereal by-products by employing biotechnological approaches such as the production of microbial enzymes. By-products resulting from the secondary processing of cereals as in the case of brewing are also presented and their possible applications to the food and healthcare industries are presented. Chapter 10 discusses the impact of different types of bran and wheat germ processing by-products on bread, biscuits, and pasta making. It provides a comprehensive overview of the properties possibly involved and discusses different strategies that have been evaluated until now to counteract the detrimental effects of these additives on bread making. For instance, cereal brans can be used as food ingredients with no supplementary costs in baked products as natural sources of dietary fibers. However, addition of cereal brans in amounts that can bring healthy benefits causes problems in bread quality, e.g., reduced volume, elasticity, and bitterness. An important factor that favors bitterness in baked products is rancidity as a result of lipid hydrolysis and fatty acid oxidation that give off-flavors. Lipid hydrolysis has an impact on the stability of food products during storage, e.g., bran's color is often dark affecting consumers' acceptance. Finally, Chapter 11 provides an overview of the previous chapters and describes future perspectives in the field.

Conclusively, the book provides a handbook for agricultural and food engineers who work in the cereal manufacturing industry and are seeking to improve their environmental management by actively utilizing waste streams in effective applications. It addresses researchers, specialists, chemical engineers, professionals, and new product developers working in the food and cereals industries. It could be used as a textbook for ancillary reading at graduate and postgraduate levels, or as multidiscipline courses dealing with agricultural science, food, and cereal chemistry, as well as food and bioresource technology. It could become a target reference for libraries and institutes dealing with cereal production all around the world (e.g., China, the United States, the Russian Federation, Brazil, Argentina, Indonesia, Australia, Canada, etc.).

At this point, I would like to thank all the authors of the book for their fruitful collaboration and creative work in bringing together topics and sustainable applications of cereal processing by-products in one cohesive and comprehensive manuscript. Their acceptance of my invitation, as well as their dedication to editorial guidelines, and the book's concept and timeline are highly appreciated. I consider myself fortunate to have had the opportunity to collaborate with so many knowledgeable colleagues from Greece, Ireland, Italy, Mexico, Poland, Portugal, Romania, Serbia, Turkey, and the United Kingdom. In addition, I would also like to thank the acquisition editor Megan Ball and the book manager Jackie Truesdell for their assistance during editing and all the team at Elsevier during the production process.

I would also like to acknowledge the support and expertise of the Food Waste Recovery Group of ISEKI Food Association that indicated the relevant experts and provided us with insights in the field. The ability of the group to support food and beverage industries to recover food waste and improve their sustainability is one of a kind. Last but not least, a message for the readers. In such a big collaborative project, it is impossible to avoid minor errors or gaps. For any mistake in or objection to the content of the book, please do not hesitate to contact me. Instructive comments and even criticisms are and will always be welcome.

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Introduction to cereal processing and by-products

1

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1.1 Cereals

Cereal crops provide essential nutrients and energy in the everyday human diet through direct human consumption and also via meat production since they comprise a major livestock feed. According to the Food and Agriculture Organization, total crop production during 2016 reached 2577.85 million tons, whereas the production of coarse grains (cereal grains other than wheat and rice used primarily for animal feed or brewing) reached 1330.02 million tons (FAO-AMIS, 2017). The term "cereals" refers to members of the Gramineae family and determines nine species: wheat (*Triticum*), rye (*Secale*), barley (*Hordeum*), oat (*Avena*), rice (*Oryza*), millet (*Pennisetum*), corn (*Zea*), sorghum (*Sorghum*), and triticale, which is a hybrid of wheat and rye. The top cereals produced in the world in 2014, ranked on the basis of tonnage (in million tons), are corn (1253.6), rice (paddy, 949.7), wheat (854.9), barley (146.3), oat (23.2), and rye (15.8) (FAOSTAT, 2017).

Cereal processing represents an important part of the food production chain, but the contribution of cereals to the nonfood sector should not be overlooked. Milling represents the principal procedure in the cereal industry and is classified in two categories: dry and wet, while each has its own characteristics. Dry milling separates the outer fibrous materials and germ, which are considered by-products of the grain endosperm. Dry milling can also refer to pearling, which is an abrasive technique that gradually removes the seed coat (testa and pericarp), aleurone and subaleurone layers, and the germ to obtain polished grain (rice, oat, and barley) and by-products with high concentration of bioactive compounds. On the other hand, wet milling is mainly used for the production of starch and gluten, having as coproducts steep solids (rich in nutrients valuable for the pharmaceutical industry), germ (intended for the oil-crushing industry), and bran. Malting is a process intended for the production of beer and other alcoholic beverages when fermentable sugars and starch of the grain (most usually barley) are consumed by enzymes, leaving behind spent grain.

1.2 Dry milling

Dry milling of cereals is one of the oldest methods of the milling industry to provide milled fractions of cereal grains. Cleaning and conditioning of grains precede milling.

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Cleaning is important because, generally, grain received in bulk contains grain impurities that depend on the type of cereal. The main grain impurities following formal definition are shriveled grains, other cereals, grains damaged by pests, grains in which the germ is discolored, sprouted grains, miscellaneous impurities such as extraneous seeds, damaged grains, extraneous matter, husks, ergots, decayed grains, dead insects, and other undesirable material (The European Commission, 2009). Cleaning employs equipment such as a magnetic separator that removes ferrous metal particles, disc or sieve separators that remove almost anything else too big or too small to be the desired grain (i.e., straw), an aspirator to remove lighter impurities (i.e., dust), a destoner that separates materials with different densities (e.g., stones) but of the same size as the desired grain, color sorters, etc.

Conditioning or tempering is the process during which the kernels are moistened with controlled addition of water for the inner endosperm to become softer and the bran harder. This process aims to prevent breakup of bran, helps gradual separation during milling, and also improves sieving efficiency. The grains are held in appropriate containers for a period of time to allow complete hydration. Generally, the soaking time and temperature of grain kernels can vary depending on the type of grain, the variety, and also the initial moisture level. For hard or vitreous kernels such as durum, conditioning is performed in two sequential steps. The final moisture and conditioning time required for hard wheat is higher than that required for soft wheat (Posner and Hibbs, 2005). Other cereals such as rye and triticale have a softer endosperm compared to durum wheat and are conditioned to lower moisture contents. Corn kernels may need up to three stages of moistening to reach the desired final moisture (18%–27%) followed by resting time in tempering chambers (Brekke, 1970). The size and shape of the grain, the way outer layers stick to endosperm, and hardness are grain characteristics of great importance in milling. Dry milling consists of two processes: grinding and sifting.

1.2.1 Corn (Zea mays *L*) (*Fig. 1.1*)

Degermination represents an extra process step (dry or wet) that takes place on corn whenever low-fat and high-purity finished products are needed. It aims to efficiently separate germ and pericarp. Following the degermination process, kernels are dehydrated to a moisture content of approximately 14% and then most of the remaining pericarp and germ are separated by air aspiration and gravity separators, respectively.

Next is the rolling and sifting step. The remaining corn kernel without the germ and a great part of the pericarp is milled to fine particles by roller mills. During rolling, in addition to endosperm pieces, small pericarp and germ species and tip caps that are still present after degermination are gradually released. These pieces are separated from the endosperm fraction through sifting, aspirating, and roller milling using a specific gravity table or purifiers (Brekke, 1970; Duensing et al., 2003).

In general, dry milling of corn results in a great number of products and by-products. Despite different attempts to classify and define products of maize processing, a global terminology for dry-milled maize products is not yet standardized (Eckhoff, 2010).

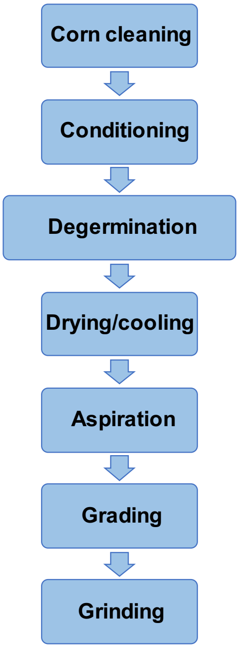

Figure 1.1 Flow chart of the corn dry milling process.

From the refined endosperm, flours of different particle size are obtained and are widely used to produce brewer's grits, snack food grits, and corn flour.

1.2.2 *Rice* (Oryza sativa *L.) (Fig. 1.2)*

1.2.2.1 Husking and paddy separation

In a modern rice mill, awns of the paddy grains are eliminated before husking. The process is named deawning and is performed for easy conveying in the elevators, chutes, and hopper offices (Alizadeh et al., 2012). Husk present in paddy rice is not considered edible, therefore it is removed. The cleaned batch of paddy rice (no need for conditioning) is sent to a dehusker where husk is separated by means of rubber rollers or steel hullers. The efficiency of the husking process is dependent on the tightness of the husk bound to the rice as a result of the rice variety and grain humidity. Husks are aspired by an air-trap aspiration system and trapped in the coarse sieve, whereas rice passes through (Bond, 2004).

The brown rice is then separated from the rough paddy rice using paddy separators that separate the product based on the difference in density, size, surface smoothness, and buoyancy into three parts, i.e., brown rice, paddy rice, and a mixture of both. Paddy rice is lighter, longer, wider, and thicker than brown rice, whereas brown rice has a smoother surface and a greater bulk density. Paddy rice is sent back for husking, the mixture is returned to the separator, whereas brown rice is fed to the pearling machines (Arendt and Zannini, 2013; Singh et al., 2013).

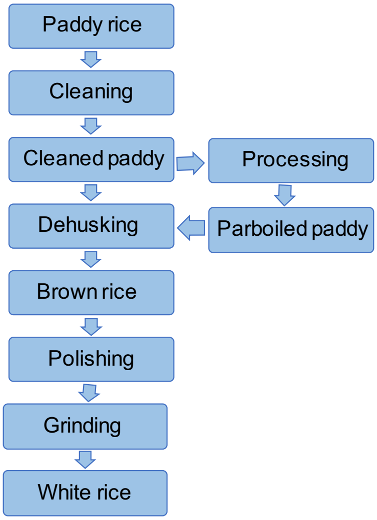

Figure 1.2 Flow chart of the rice dry milling process.

1.2.2.2 Pearling, polishing, and grading

During pearling the bran is removed from the rice kernel by intensive mechanical and thermal stress. The pearling machines can use an abrasive or friction process for bran removal. Weather conditions during the crop year, storage conditions, as well as grain type affect the whiteness of the rice grain. The stress applied during whitening causes some rice kernel damage and breakage. Chalkiness increases the possibility that kernels are broken during milling (Singh et al., 2013). The loose bran, which is stacked to the surface of the rice after the pearling process, is removed during a polishing step.

Polishing is performed by a mild friction or abrasion created by a rubber polisher that polishes the pearled rice using a rubber brush (Arendt and Zannini, 2013; Singh et al., 2013). Under gentle brushing the remaining bran is removed and the rice kernels achieve better translucency.

The removed bran is collected by aspirators, whereas the polished rice is graded since it contains different-sized broken rice pieces, bran, and dust. During grading the small broken rice pieces are separated by a vibrating sieve, whereas the remaining bran and dust particles are separated by air aspiration (Arendt and Zannini, 2013; Bond, 2004).

Rice differs from other cereals since it is mainly consumed as an intact grain. Therefore the rice-milling industry is focused on the decrease in the percentage of broken kernels. According to Shitanda et al. (2002) the physical and mechanical properties of rice varieties affect the milling quality (i.e., head rice yields and degree of milling). The physical factors affecting the degree of milling are hardness, size and shape, and surface ridge on the grain (Liu et al., 2009).

1.2.2.3 Grinding and sifting

Grinding of polished rice is performed using machinery such as a hammer mill, pin mill, roller mill, disc mill, etc. (Arendt and Zannini, 2013). Flour is produced from whole or broken grains. Rice flour is used in a great number of products such as infant formulas or processed products (i.e., rice noodles or vermicelli). Nowadays, rice flour is used in baking to replace wheat flour in gluten-free products since rice does not contain gluten (Papageorgiou and Skendi, 2015).

1.2.3 Wheat (Triticum sp.) (Fig. 1.3)

After conditioning, the wheat kernels are first passed through an abrasive machine that eliminates impurities present on the pericarp and break-damaged kernels. Two types of roller mills, break and reduction roller mills, are involved in the milling of wheat kernels.

First, break rollers break the wheat kernel and remove the endosperm and germ from the pericarp. The break material consists of bran, sizings (the coarsest part of the endosperm), middlings (finer particles of endosperm that require further reduction to yield the flour), and break flour fractions. The separation of milled wheat kernels is usually performed with sifters and purifiers. Purifiers can remove bran and produce

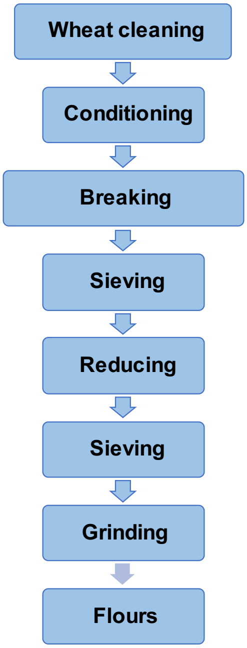

Figure 1.3 Flow chart of the wheat dry milling process.

more refined flours from middlings with lower ash content and better color scores (Posner and Hibbs, 2005). Properties of wheat kernels such as moisture content (Fang and Campbell, 2003), hardness (Campbell et al., 2007), shape (Fuh et al., 2014), and uniformity within the kernel are the main factors that affect the size distribution of middlings (Warechowska et al., 2016).

Second, the reduction rolls reduce further the sizings and middlings into flour. The resulting flours may have different color hues, degree of damaged starch, and ash content. The quality of the resulting products is dependent on the wheat characteristics as well as the milling procedure conditions (Baasandorj et al., 2015; Campbell et al., 2001, 2007).

The same basic principles of flour milling are applied to durum wheat for the production of durum semolina. Semolina is coarser than wheat flour and is usually used for pasta production.

Pearling as described in Section 1.2.2 is the process of progressively removing the outer layers of the cereal grains. The industry also uses this technology in wheat flour milling because it lowers the capital investment costs, giving the benefit of better quality products (Dexter and Wood, 1996; Mousia et al., 2004). Removal of the outer kernel layers to a desired level prior to milling means less bran to be removed during the subsequent milling process, fewer stages, and better flour and semolina yield (Dexter and Sarkar, 2004). The removed layers during pearling are called pearlings.

1.2.4 Other cereals

Milling of rye (*Secale cereale*), triticale (*Triticum secale*), or barley (*Hordeum vulgare*) is performed following the same principles described earlier for the milling of wheat.

Milling of oats (*Avena sativa*) requires a thermal treatment and then a dehulling step of the grains to produce naked caryopses known as groats before milling. After cleaning, oats are thermally treated to inactivate endogenous enzymes (i.e., lipases and lipoxygenases), and prevent the development of rancidity, off-flavors, and off-odors in the resulting flours. Heat treatment reduces enzyme activity and allows better removal of the glumes during subsequent dehulling (Deane and Commers, 1986). A dehulling step follows and finally a mixture of groats, free hulls, unhulled oats, broken kernels, and fines is produced. The fines and hulls are removed by air aspiration, whereas unhulled oats are removed by separators. The recovered oats are conveyed once again to the dehulling machines. Hulls account for 25% of the yield, whereas the rest is groats (Deane and Commers, 1986). Different millers choose to perform conditioning of the separated groats before milling. Finally, groats are cut and flaked, and then sent to a milling unit if needed to be grounded into meal or flour with break roller mills and/or hammer mills. The resulting meal is usually sifted, and the coarse particles are recycled to the mills (Deane and Commers, 1986). In addition to the oat meal and flour, groats can be cut and flaked for the production of rolled oats.

1.3 Wet milling

In contrast to dry milling, wet milling consists of grinding the soaked grain and then separating the grain chemical compounds (starch, proteins, fiber, and oil). Wet milling of mainly corn aims to extract the maximum possible amount of native or undamaged starch granules. Therefore starch represents the primary product of wet milling. It is produced in the form of regular, waxy, and high-amylose starch depending on the amylose content of the primary source. In the food industry, starch is used mainly to produce syrups (i.e., maltodextrins, glucose, etc.), other modified starches, thickeners, bakery and confectionary products, soups, baby foods, and brewing adjuncts. From an economical point of view, conversion of the starch obtained during mainly corn wet milling to sweeteners and ethanol represents its main use. The pharmaceutical industry is also an end user of the products derived from starch. Moreover, starch finds many nonfood applications in the textile industry, such as packaging material and in the production of adhesives, etc.

The wet milling process involves different physical, chemical, biochemical, and mechanical operations. This process is used industrially primarily for corn and secondarily for wheat but it could also be successfully applied to other cereals such as sorghum, barley, and oats. Yet every cereal grain can be wet milled if appropriate modification of the equipment or processing is made. Similarly to dry milling, cleaning of grains represents the first step of the wet milling process of all cereal grains. Steeping is the next critical step followed by grinding of soaked kernels and shifting.

1.3.1 Steeping

Steeping of corn usually lasts from 30 to 48 h. Steeping is performed by soaking the kernels in a warm solution containing sulfur dioxide, which is used as a reducing agent to soften the corn endosperm structure. The final moisture content during this step reaches around 48%–50% of the kernel weight. During steeping 5%–7% of corn solids (mainly albumins and globulins, lactic acid, minerals, phytic acid, and vitamin B) are solubilized (Johnson and May, 2003). Proteins soluble in the steeping solution may be recovered by filtration or centrifugation after adjusting the pH value.

Steeping of wheat kernels depends on the selected process. Mainly, the Alsatian and Halle processes are applied to wheat kernels, whereas other processes use white flour produced from dry milling (Van Der Borght et al., 2005). When Halle fermentation is applied, wheat kernels are steeped in water for about a week at 25°C to soften the grain (Van Der Borght et al., 2005). In the Alsatian process, steeping is carried out at 30–35°C and lasts 1–2 days (Kempf and Röhrmann, 1989; Knight and Olson, 1984; Van Der Borght et al., 2005). Steeping of wheat grains under pressure (Meuser et al., 1989) or breaking the wet grains prior to steeping (Kema et al., 1996) reduces the steeping time considerably. Moreover, phytin-degrading enzymes, cellulose, or preparations containing a mixture of xylanases, acidic protease, cellulose, and arabinofuranodase during steeping are proposed to improve wet milling efficiency (Van Der Borght et al., 2005).

1.3.2 Corn grinding and sifting (Fig. 1.4)

After steeping comes the first milling step, where the moistened corn kernels are wet milled in plate or disc attrition mills into large pieces so that the germ is released. The germ is separated in hydrocyclones to a less dense rubbery type compared to the rest of the kernel, and is then dewatered and dehydrated to be used for oil extraction (Johnson and May, 2003).

During the second milling step the denser endosperm pieces that may also contain pericarp tissues are milled to release the pericarp in flakes. Pericarp pieces are separated in a metal sieve, whereas the endosperm particles are milled into fine slurry to release the starch granules from the protein matrix. Wet milling aims to release starch granules with minimal mechanical damage. Next, proteins are separated from starch granules by centrifugation and further purification. The resulting refined starch and proteins are dehydrated to a final moisture content of 6% and 12%, respectively (Watson, 1984).

1.3.3 Rice grinding and sifting

Following the steeping procedure, rice is passed to mills and allowed to rest for up to 24 h. The fiber is then removed by screening, whereas the starch, the main wet milling product of rice, is first recuperated by centrifugation and then washed with water to remove excess alkali and finally dried to a final moisture content of 10% (Juliano, 1984). Centrifugation wastes contain proteins that could be recovered following the same procedure for the recovery of proteins in the steeping water.

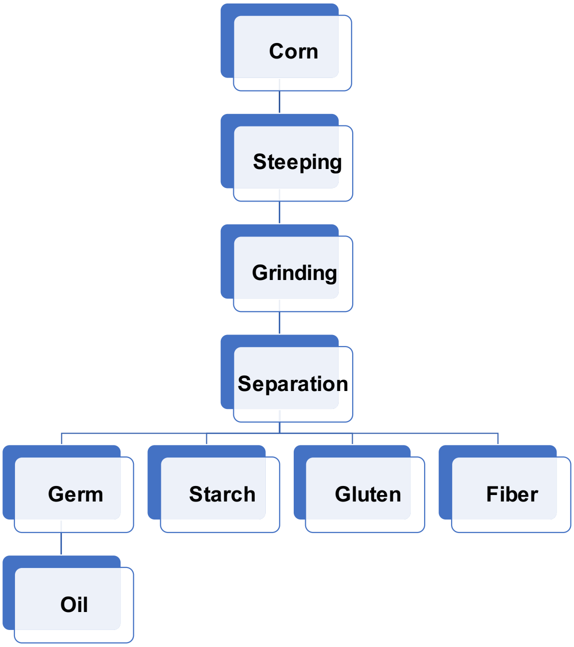

Figure 1.4 Corn wet milling process.

1.3.4 Wheat grinding and sifting

Important quantities of wheat are directed to wet milling industries to produce vital gluten and starch. Wet milling methods differ in the size of the aggregated protein particles from a mixture of flour and water initially subjected to fractionation and in the mode of separating starch from gluten (Robertson and Cao, 1998). All traditional wheat wet milling processes begin with the production of unoptimally developed stiff dough or batter, whereas current modern methods utilize flour or dough water dispersions with partially developed gluten. Many different processes have been established for the industrial production of wheat starch and wheat gluten from wheat kernels or refined flours: Halle, Martin, dough-batter (hydrocyclone), batter, Fesca, Alfa-Laval/Raisio, high-pressure disintegration process, and others (Kempf and Röhrmann, 1989).

Halle fermentation dictates that the steeped wheat is grinded and the mash is fermented to degrade or solubilize the proteins. Starch is washed out, whereas the bran and protein fractions are retained in perforated drums (Kempf and Röhrmann, 1989). The starch is refined and dried (Kempf and Röhrmann, 1989; Knight and Olson, 1984), whereas the vital gluten is destroyed and cannot be recovered (Kempf and Röhrmann, 1989).

The Martin method is recognized as the oldest wet milling process to isolate wheat starch and vital wheat gluten. In this method, refined flour and water (ratio 2:1) are mixed to form a properly developed dough where gluten is dissociated from starch and forms a gluten protein network (Serna Saldivar, 2013). Then, starch is washed out from the gluten network with water without breaking the gluten into small particles. Washing waters that contain starch and some soluble compounds such as soluble proteins and carbohydrates pass through sieves, whereas the insoluble wet gluten is retained. The obtained gluten is carefully dehydrated to 8% moisture content. The starchy washings are separated in rotary sieves from contaminants (fibers and small gluten pieces) and dried. The purified starch slurry is then separated in A and B starch granules based on their density and then dried to a final moisture content of 10%. Beside vital gluten and starch, the Martin process yields inseparable starch and other proteins from the washings (Maningat et al., 2009; Serna Saldivar, 2010).

The dough-batter process (industrially known as the hydrocyclone method) utilizes refined wheat flour and warm water to form slack dough that after a short period of resting is homogenized with water at a high shear rate in an agitated tank. From the slurry, three phases are obtained after decanting: a starch-rich slurry, a mixture of gluten and B starch granules, and an insoluble protein. In the decanter, the insoluble gluten is retained by the screens thus separated, washed and finally dried. Washing waters of gluten contain starch, bran, and cell wall debris. Subsequently, the starch slurry is sent in a set of hydrocyclones and screened to remove fine fibers and obtain a rich A starch fraction that is concentrated and dried. The mixture of B starch and gluten is screened resulting in a slurry rich in B starch and wet fiber (mostly pentosans) that is subsequently dried (Maningat et al., 2009; Serna Saldivar, 2013).

High-pressure disintegration is based on starch extraction and separation by centrifugal forces from a highly sheared batter. Refined wheat flour is mixed with warm water in a continuous dough mixer to achieve a smooth batter that is pumped at high pressure. This step allows starch granules to be released from the hydrated gluten network that is disrupted into tiny particles. Water addition dilutes the homogenized batter that is sent to a three-phase decanter that separates and concentrates each phase based on decreasing density as follows: A starch stream, B starch and gluten-rich stream, pentosans, and other soluble contaminants containing a viscous stream. The high yield of A starch and low water consumption are the main advantages of this process.

1.3.5 Other cereal wet milling

According to Serna Saldivar (2013), wet milling on an industrial scale for the production of rye, triticale, barley, and oat starches is very limited or practically nonexistent today. The extraction of starch from rye is difficult because of its higher pentosan content and poor gluten-forming ability. Similarly, the wet milling of oats is limited due to difficulties in the complete separation of the starch because of the hydrated bran and protein layers. Difficulties occur in the separation of barley starch due to high β-glucan content that induces high viscosities in aqueous solutions and makes the separation of starch by screening and centrifugation difficult. Wet milling of triticale can be performed following any of the wheat wet milling technologies.

1.4 Malting (Fig. 1.5)

The technologies of malting and brewing vary widely, resulting in a variety of products. Malting is primarily applied to barley grains following cleaning and grading of the grains into uniform fractions, which are then properly stored and processed. The production of malt comprises the following processes: steeping, germination, and kilning. Malting uses the ability of natural germination when the barley grain, completely free from dormancy, germinates after absorbing water in the presence of oxygen to reach a moisture content of up to 47% (Kunze, 2004). The floating kernels are not suitable for malting and represent a by-product. When barley absorbs water the embryo is activated and uses the oxygen that is dissolved in the steeping water and the one supplied for breathing. During the germination process the barley embryo grows and rooting starts. Germination and steeping processes often overlap. Germination time and temperature affect root growth: the longer and warmer the germination, the longer the roots and the greater the malt yield losses. To minimize the losses, germination time and temperature are kept as low as possible (Kunze, 2004). During germination, enzymes that are contained in the barley kernels begin to break down the endosperm high molecular weight material from the yeasts into easily digested components. The germination process is broken up by drying the malt and kilning to stop further transformations. During drying, the water content is decreased to less than 5%, thus stopping all the enzymatic activity while color and flavor compounds are formed. After kilning, the roots are cut off and removed and the resulting malt is properly stored. In addition to barley, other cereals such as wheat and rye are occasionally used to make malt. Although malt is mainly used as a first ingredient to produce beer and whisky it has found application in the production of meals, malted shakes, malt vinegar, confections, flavored drinks, and baked goods.