CHAPTER

12

Malting, brewing, fermentation, and distilling

OUTLINE

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12.1 INTRODUCTION

The overall process involved in brewing and fermentation is the conversion of cereal starch into alcohol to make a variety of palatable intoxicating beverages, generally on a small to moderate production scale – some at a factory level, but much at a household or village level. Production, marketing and sales of alcohol-based drinks are vast on a global scale. For example, in 2015 the global sales of beer were estimated to be worth US$ 522 billion, with a total volume of 1.9×10^9 hL. Of this, 471.6×10^6 hL were produced in China, 223.5×10^6 hL were produced in the United States, 138.6×10^6 hL were produced in Brazil and 95.6×10^6 hL were produced in Germany (Statista, 2017). In terms of distilled spirits, in 2010 the global market was worth nearly US$ 91 billion, with 31% of sales being whiskey/whisky, 22% vodka, 12% rum and 35% other (including gin, liquors, white spirits, tequila, etc.) (Ibis, 2010).

Fermentation is also used on a massive scale (compared to beverage production) to produce nonpotable industrial alcohols (e.g., biofuels) in production facilities much larger than breweries or distilleries.

Yeasts appropriate to the cereal or cereals involved actually conduct the fermentation process. Most commercial yeasts belong to the species *Saccharomyces cerevisiae* (Fig. 12.1), which now includes the 'bottom yeast' previously classified as *S. carlsbergensis* (Reed and Nagodawithana, 1991), and actually consists of several thousand specific strains.

Two key processes are involved in fermentation: first, the starch has to be converted to soluble sugars by amylolytic enzymes, and second, these sugars must be fermented to alcohol by yeast metabolism (i.e., yeasts do not ferment starch, rather they ferment glucose). In the first process the enzymes may be produced in the grains themselves (endogenously) or exogenously, i.e., in other organisms, and are then added to the fermentor or upstream of the fermentor. Alternatively they may be added as extracts.

The process by which the grain's own enzymes are employed is known as 'malting'. This involves controlled germination of the grain during which the enzymes capable of catalysing hydrolysis, not only of starch but also of other components of the grain, are produced. The most significant

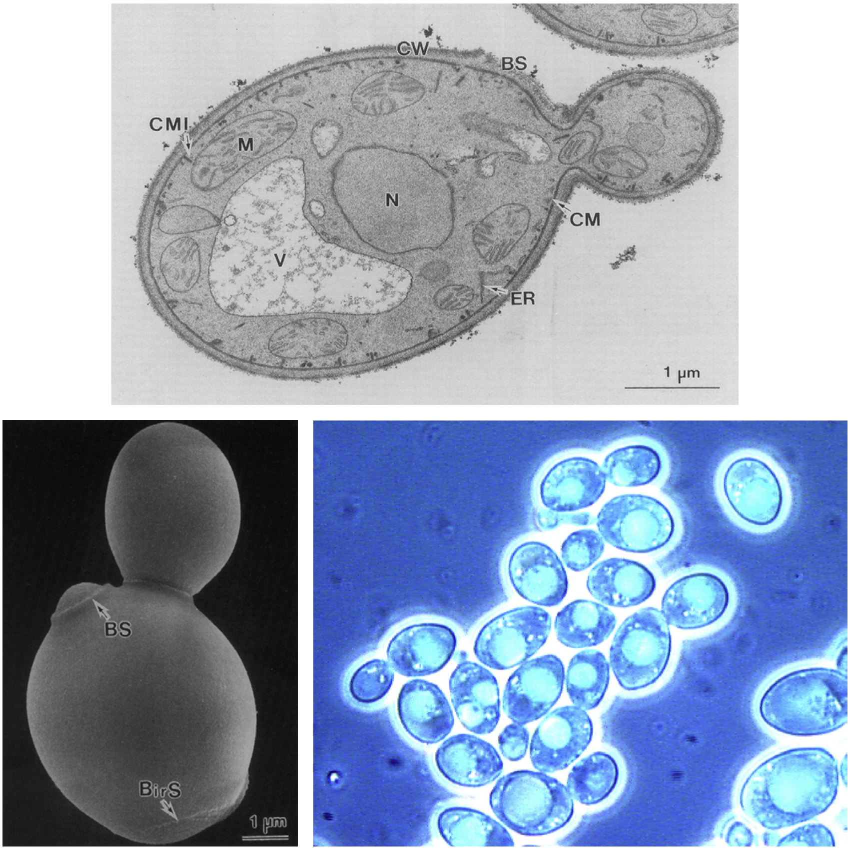


FIGURE 12.1 *Saccharomyces cerevisiae*, the most important industrial yeast, is used for the fermentation of beers, distilled spirits and biofuels. Top shows interior view of a yeast cell. *BS*, budding scar; *CM*, cell membrane; *CW*, cell wall; *ER*, endoplasmic reticulum; *M*, mitochondria; *N*, nucleus; *V*, vacuole. Bottom left image shows a budding cell and budding scar. *Images courtesy of Walker, G., Abertay University, Scotland, UK.*

are the proteases and the β-glucanases, as the products resulting from their activities ultimately affect the qualities of the beverage produced.

Other organisms are employed as a source of enzymes in the production of saké – a beer produced from rice. Enzymes are added in solution, particularly when it is required to hydrolyse the starch, etc. present in endosperm grits or flours, themselves incapable of enzyme production. Such adjuncts may provide any proportion of the total starch, depending on legislation relevant to the country of origin and the description of the alcohol product. Consequently, added enzymes may contribute different proportions of the enzyme complement.

The alcohol content of the liquor produced by fermentation is limited by the tolerance of the yeasts. Probably the most tolerant yeasts are used in saké production. They can survive alcohol contents of about 20% or more in the fermentor, although the product is often sold in a diluted form.

Distillation then concentrates the alcohol into higher levels (less than 100%, though, depending upon the azeotrope), and the resulting drinks are described as 'spirits', the special character of which depends upon flavours imparted by the processing or added to the distillate – the added flavours usually being extracts from other plant sources (e.g., cinnamon, orange, juniper, etc.). In recent years infusions of novel flavours (such as bubble gum, cotton candy, honey, etc.) have become popular, especially in vodkas and whiskies.

For alcohol production from plant materials, sugars must be present, as in fleshy fruits or other substrates from which fermentable sugars can be produced. Starch is a primary substrate (from which sugars can be produced by enzymes) in many cultures; and in fact all cereal grains can be used for alcohol production. In the West, the most commonly used cereal grains are barley, maize and wheat, but substantial quantities are derived from other grains around the world, such as wheat (for vodka), maize (for beer in central America and Africa), rye (for whiskey in the United States and *kvass* in Eastern Europe and former Soviet states), rice (for saké in Japan, *shaoshinchu*, *baijiu* and *shaojiu* in China and *soju* in Korea) and sorghum (for beer in Africa). Triticale may be used as an adjunct in beers as well. A few examples of alcohol-based drinks from around the world, and the microorganisms which are used for their fermentations, are provided in Table 12.1.

This chapter discusses the processes of malting, beer and spirits production and biofuels production.

TABLE 12.1 Some examples of cereal-based alcohol drinks from around the world and microorganisms used

Cereal grain	Drink	Microorganisms	Common locations
Barley	Beer	*Saccharomyces cerevisiae*	Worldwide
	Tella (beer)	*Lactobacillus pastorianumi*, *S. cerevisiae*	Eritrea, Ethiopia
	Whisky/whiskey	*S. cerevisiae*	China, Europe, India, Japan, United States
	Yakju (beer or wine)	*Aspergillus usamii*, *S. cerevisiae*	Korea
Maize	Busaa (beer)	*Lactobacillus plantarum*, *S. cerevisiae*	Kenya
	Chicha (beer)	*Lactobacillus* spp., *S. cerevisiae*	Central and South America
	Kaffir (bantu beer)	*Lactobacillus* spp., *S. cerevisiae*	Africa
	Munkoyo (beer)		Zambia

TABLE 12.1 Some examples of cereal-based alcohol drinks from around the world and microorganisms used—cont'd

Cereal grain	Drink	Microorganisms	Common locations
	Pito (beer)	*Candida*, *Lactobacillus*, *Leuconostoc*, *Saccharomyces* spp.	Ghana, Nigeria
	Tella (beer)	*L. pastorianumi*, *S. cerevisiae*	Eritrea, Ethiopia
	Tesguino (beer)	*Bacillus megaterium*, *S. cerevisiae*	Mexico
	Urwaga		Kenya
	Whiskey	*S. cerevisiae*	USA, worldwide
	Yakju (beer or wine)	*A. usamii*, *S. cerevisiae*	Korea
Millet	Baiju (*shaojiu*)		China
	Busaa (beer)	*L. plantarum*, *S. cerevisiae*	Kenya
	Ikigage		Rwanda
	Kaffir (bantu beer)	*Lactobacillus* spp., *S. cerevisiae*	Africa
	Mbege	*L. plantarum*, *S. cerevisiae*	Tanzania
	Munkoyo (Ibwatu beer)		Zambia
	Tella (beer)	*L. pastorianumi*, *S. cerevisiae*	Eritrea, Ethiopia
	Thumba	*Endomycopsis fibuliger*	Bengal
	Urwaga		Kenya
Rice	Hong-ru (wine)	*Rhizopus javanicus*, *Monascus purpureus*, *S. cerevisiae*	China, Taiwan
	Madhu (wine)		India
	Ruhi	*Lactobacillus*, *Mucor*, *Rhizopus* spp.	India
	Saké (wine)	*A. oryzae*, *L. sake*, *Pseudomomonas nitroreducens*, *S. cerevisiae*	China, Japan, Taiwan
	Shaoshinchu		China
	Soju/shochu	*R. javanicus*, *S. peka*	Canada, China, Japan, Korea, Taiwan, United States
	Tapé	*Amylomyces rouxii*, *Endomycopsis burtonii*, *R. chinensis*	China, Indonesia, Malaysia

Continued

TABLE 12.1 Some examples of cereal-based alcohol drinks from around the world and microorganisms used—cont'd

Cereal grain	Drink	Microorganisms	Common locations
	Tapuy (wine)	*Endomycopsis fibuliger*	Philippines
	Yakju (beer or wine)	*A. usamii*, *S. cerevisiae*	Korea
Rye	Kvass (beer)		Russia, Eastern Europe
	Whiskey	*S. cerevisiae*	Europe, United States
Sorghum	Burukutu	*Lactobacillus*, *S. cerevisiae*	Nigeria
	Busaa (beer)	*L. plantarum*, *S. cerevisiae*	Kenya
	Ikigage		Rwanda
	Kaffir (bantu beer)	*Lactobacillus* spp., *S. cerevisiae*	Africa
	Mwenge	Uganda	
	Pito (beer)	*Candida*, *Lactobacillus*, *Leuconostoc*, *Saccharomyces* spp.	Ghana, Nigeria
	Sekete		Nigeria
	Tella (beer)	*L. pastorianumi*, *S. cerevisiae*	Eritrea, Ethiopia
	Urwaga		Kenya
Teff	Tella (beer)	*L. pastorianumi*, *S. cerevisiae*	Eritrea, Ethiopia
Wheat	Bousa (beer)	*Lactobacillus*, *S. cerevisiae*	Egypt
	Beer	*S. cerevisiae*	Worldwide
	Shaoxing (*sao-hsing*, rice wine)	*A. oryzae*, *A. rouxii*, *Rhizopus* sp., *S. cerevisiae*	Asia
	Tella (beer)	*L. pastorianumi*, *S. cerevisiae*	Eritrea, Ethiopia
	Whiskey	*S. cerevisiae*	United States, worldwide
	Yakju (beer or wine)	*A. usamii*, *S. cerevisiae*	Korea

Based upon data from Gelinas, P., Mckinnon, C., 2000. Fermentation and microbiological processes in cereal foods (Chapter 26). In: Kulp, K., Ponte Jr., J.G. (Eds.), Handbook of Cereal Science and Technology. Marcel Dekker, Inc., New York, NY, USA; Kubo, R., Kilasara, M., 2016. Brewing techniques of Mbege, *a banana beer produced in Northeastern Tanzania. Beverages 2 (21), 1–10; Lee, M., Regu, M., Seleshe, S., 2015. Uniqueness of Ethiopian traditional alcoholic beverage of plant origin, tella. Journal of Ethnic Foods 2, 110–114; Papas, R.K., Sidle, J.E., Wamalwa, E.S., Okumu, T.O., Bryant, K.L., Goulet, J.L., Maisto, S.A., Braithwaite, R.S., Justice, A.C., 2010. Estimating alcohol content of traditional brew in Western Kenya using culturally relevant methods: the case for cost over volume. AIDS Behaviour 14 (4), 836–844; Lyumugabe, F., Uyisenga, J.P., Songa, E.B., Thonart, P., 2014. Production of traditional sorghum beer "ikigage" using* Saccharomyces cerevisiae, Lactobacillus fermentum *and* Issatckenkia orientalis *as starter cultures. Food and Nutritional Sciences 5, 507–515; and http://www.wikipedia.org.*

12.2 MALTING

During malting, large molecular weight components of the endosperm cell walls, the storage proteins and the starch granules are hydrolysed by enzymes, rendering them more soluble in water – which is especially important for grain-out-style fermentations.

All cereal grains are capable of undergoing malting, but barley is particularly suitable because the adherent pales (lemma and palea – see Chapter 3) provide protection for the developing plumule, or acrospire, against damage during the necessary handling of the germinating grains. Further, the husk (pales) provides an aid to filtration when the malt liquor is being removed from the residue of insoluble grain components. A third advantage of barley lies in the firmness of the grain at high moisture content.

Both two-row and six-row barleys (see Chapter 3) are suitable: the former are generally used in Europe, the latter in North America. Distinct varieties were formerly grown for malting, but were lower yielding than varieties grown for feeding. Modern malting varieties have high yields and are thus also suitable for the less demanding alternative uses.

Four characteristics are required of a malting type of barley.

1. High germination capacity and energy, with adequate enzymatic activity.
2. Capacity of grains modified by malting to produce a maximum of extract when mashed prior to fermentation.
3. Low content of husk.
4. High starch and low protein contents.

These qualities can be affected by husbandry and handling as well as by genetic factors: loss of germination capacity can result from damage to the embryo during threshing, or overheating during drying or storage.

Provided that grains are ripe, free from fungal infestation and intact, the yield of malt extract should be directly related to starch content.

High-nitrogen barley is unsuitable for malting, however, for four reasons.

1. Starch content is lower.
2. Longer malting times are required.
3. Modification never proceeds as far as in low-nitrogen barleys.
4. The greater quantities of soluble proteins lead to haze formation, and may provide nutrients for bacteria and thus impair the keeping quality of the beer. The average nitrogen content of malting barley is 1.5%; some 38% of this appears in the beer in the form of soluble nitrogen compounds, the proportion of the total nitrogen entering the beer being somewhat larger from two-row than from six-row types.

12.2.1 Dormancy

Harvest-ripe barley may not be capable of germination immediately. While this is advantageous in the field, protecting the crop against sprouting in the ear, it is clearly a problem in relation to malting, which depends on germination occurring. The mechanism of dormancy is not fully understood, and indeed it is unlikely that a single cause is involved in all cases; in many instances it has been shown that germination is inhibited by the inability of the embryo to gain access to oxygen. A distinct phenomenon known as 'water sensitivity' can arise during steeping if a film of water is allowed to remain on the surface of the grains. The water contains too little dissolved oxygen to satisfy the needs of the developing embryo and acts as a barrier to the passage of air. Dormancy declines with time and storage is thus not just a means of holding sufficient stocks of grain, but is an essential part of the process of malting. During the storage of freshly harvested barley tests are performed to detect the time at which dormancy has declined sufficiently for malting to commence properly. Both 'dormancy' and 'water sensitivity' are defined in relation to the test performed. In one test 100 grains are germinated on filter papers with 4 and 8 mL of water; the difference between viability and the germination on 4 mL of water is called dormancy, while the difference between the levels of germination on the different volumes of water is the water sensitivity. Factors involved in controlling and breaking dormancy were reviewed by Briggs (1978).

12.2.2 Barley malting operations

The major practical steps in malting are shown schematically in Fig. 12.2. More specific details are provided in Fig. 12.3, which illustrates a typical engineering flow diagram for a malting facility. Overall plan and section views for typical malting plants are shown in Figs 12.4 and 12.5 for horizontal and vertical facility arrangements, respectively.

Selected barley is 'steeped', usually by immersion in water, for a period chosen to achieve a particular moisture level in the grain. The water is drained from the grain, which then germinates. Conditions are regulated to keep the grain cool (generally below 18°C) and minimize water losses. As the grain germinates the coleoptile (acrospire) grows beneath the husk and pericarp while the 'chit' (coleorhiza, root sheath) appears at the base of the grain, which is split by the emerging rootlets (as illustrated in Fig. 12.6).

At certain intervals the grain is mixed and turned to provide more uniform growth opportunities and prevent the roots from matting together. As the embryo grows it produces hormones, including gibberellic acid, stimulating production of hydrolytic enzymes in the scutellum and aleurone layer which lead to 'modifications' of the starchy endosperm. The malting process is regulated by the initial choice of barley, the duration of growth, the temperature, the grain moisture content, changes in

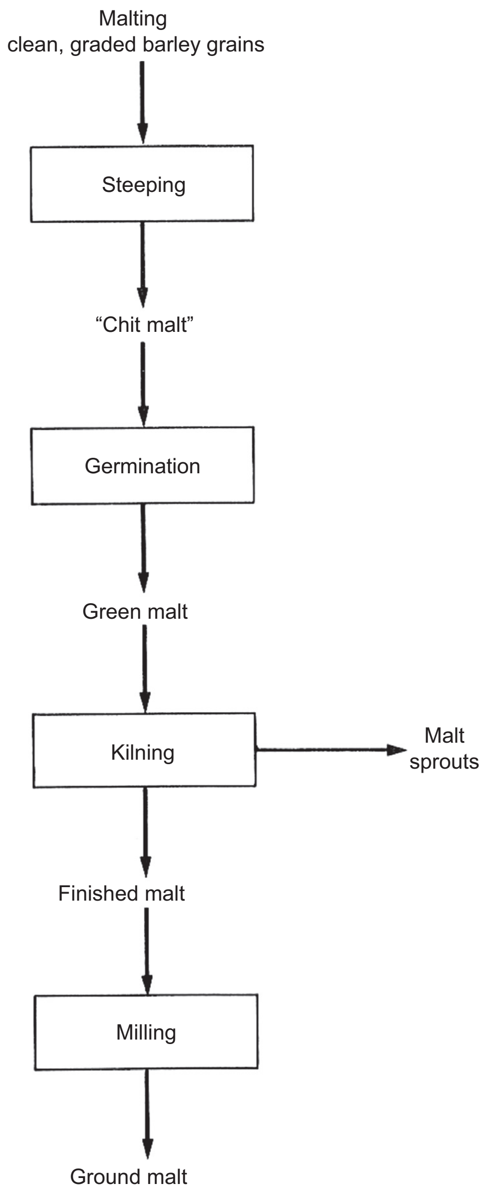


FIGURE 12.2 Flow chart summarizing the major steps in the malting process.

the steeping schedule and the use of additives. When modifications are deemed sufficient (according to intended use) the germination process is stopped by kilning the 'green malt' – that is, by drying and cooking it in a current of hot, dry air. The dry, brittle culms are then separated and the finished malt is transported to storage bins. Dry malt is stable in

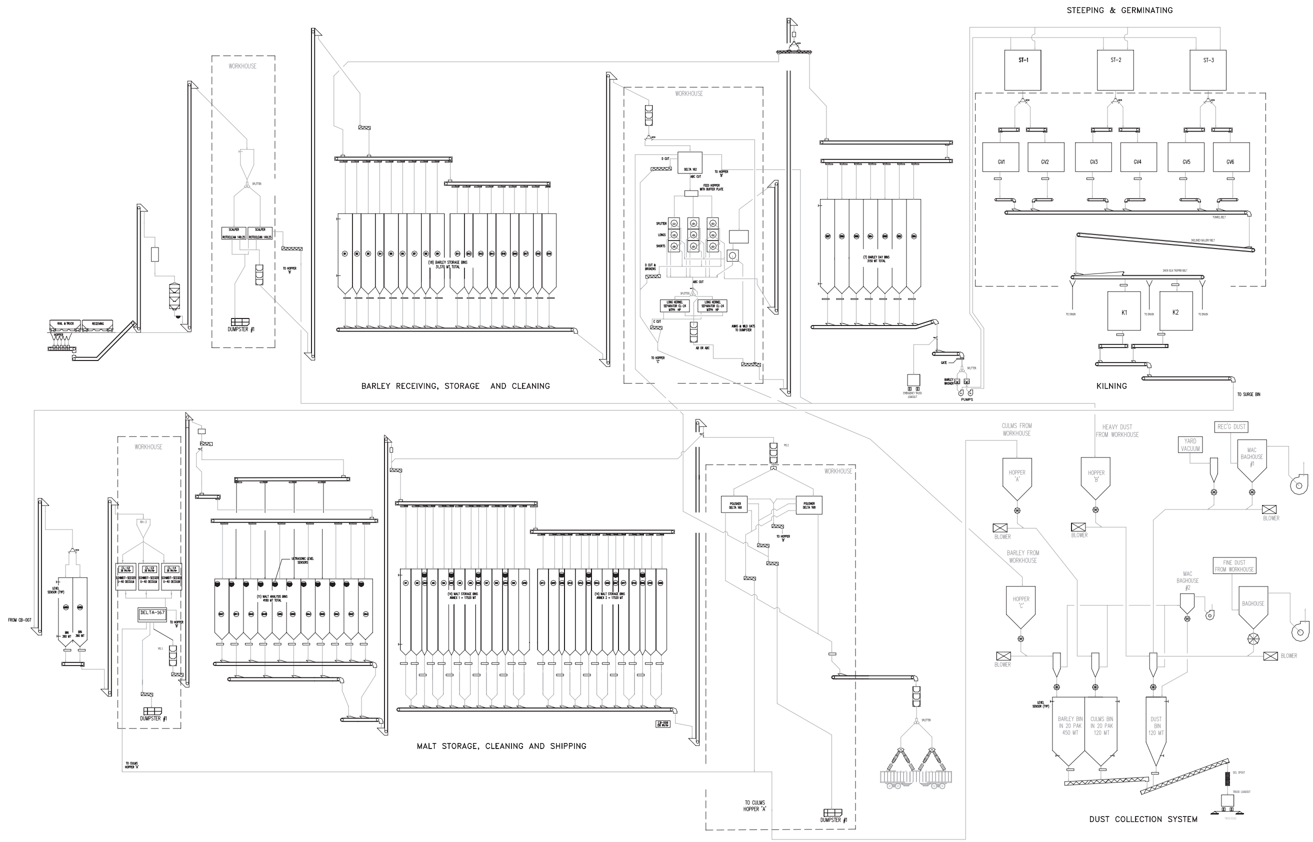


FIGURE 12.3 Process flow diagram for a typical commercial malting plant.

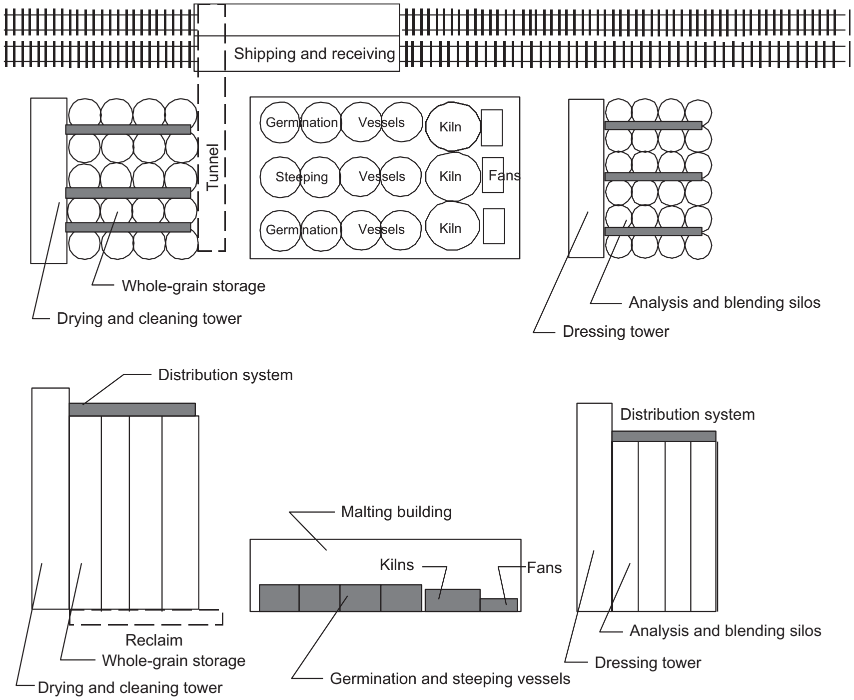


FIGURE 12.4 Plan and section views of horizontal-style malting plant layout. *Adapted from Williams, G.D., Rosentrater, K.A., 2005. Design Considerations for the Construction and Operation of Malting Facilities. Part 1: Planning, Structural, and Life Safety Considerations. Paper 054095. Annual Meeting of the American Society of Agricultural and Biological Engineers, Tampa, FL, USA.*

storage and, unlike raw barley, is readily crushed. The conditions of kilning are critical in determining the organoleptic character of the malt: it can cause a slight enhancement of the various attributes found in green malt or can completely destroy them. Malt contains relatively large quantities of soluble sugars and nitrogenous substances and, if it has been kilned at low temperatures, it contains high levels of hydrolytic enzymes. When crushed or milled malt is mixed with warm water the enzymes will then catalyse hydrolysis of the starch, other polysaccharides, proteins and nucleic acids, regardless of whether these nutrients are from the malt itself or from materials that are mixed with it. The solution of the products of hydrolysis extracted from the malt/water mixture is called the 'wort'. It forms the feedstock for fermentation for brewing or distillation (Briggs, 1978). Ultimately, malt also confers colour, aroma and flavour to the final fermented product.

One of the benefits derived from the application of engineering and technology in malting has been the reduction in resources, energy and time required to produce satisfactory malts. The amount of time saved

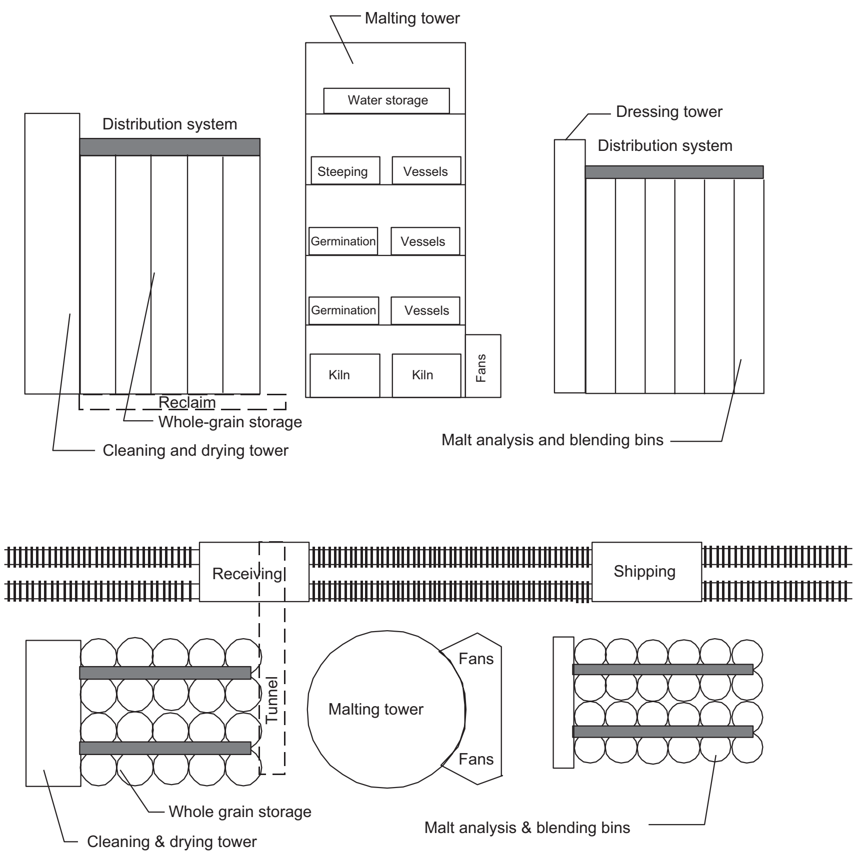


FIGURE 12.5 Plan and section views of vertical-style malting plant layout. *Adapted from Williams, G.D., Rosentrater, K.A., 2005. Design Considerations for the Construction and Operation of Malting Facilities. Part 1: Planning, Structural, and Life Safety Considerations. Paper 054095. Annual Meeting of the American Society of Agricultural and Biological Engineers, Tampa, FL, USA.*

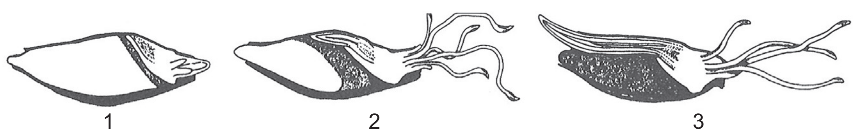


FIGURE 12.6 Diagrammatic longitudinal sections through barley grains in the early stages of germination. 1, Imbibed grain; 2, rootlets emerged; 3, rootlets and coleoptile emerged. *From Briggs, D.E., 1978. Barley. Chapman and Hall Ltd., London, UK. Reproduced by courtesy of Chapman and Hall Ltd.*

can be inferred from the diagram in Fig. 12.7. It is clear that the greatest savings have occurred during the last century and that savings are made in all stages of malting, although the greatest benefits have been achieved in the germination stage.

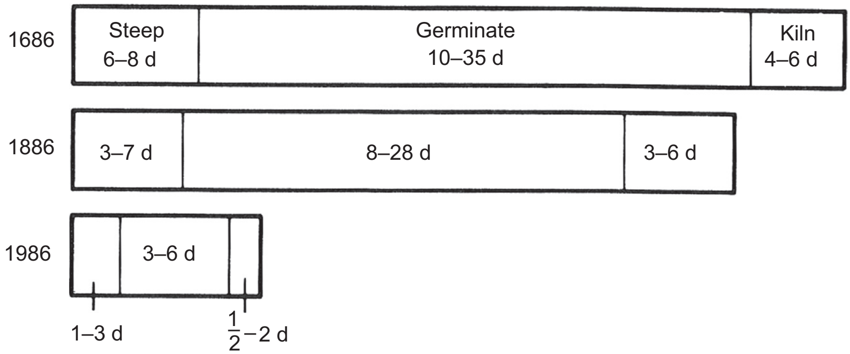


FIGURE 12.7 Diagram showing the reduction, over three centuries, in periods needed for malting and the three stages involved in the process.

12.2.3 Steeping

Traditional malting included a ditch steep followed by germination in heaps on the floor. It was a labour-intensive process, as the heaps or 'couches' required frequent manual turning, and it was very time consuming.

Current practice varies according to the size of operation and the preferences of the maltster, but self-emptying steep tanks have replaced the ditch steep. Vessels may be flat-bottomed or conical-bottomed tanks (Fig. 12.8). They have equipment for water filling and emptying, and compressed air blowers provide both aeration and 'rousing' and mixing during the steeping process. Together, these processes combine to remove carbon dioxide which accumulates as a result of respiration of grains and microorganisms associated with them. Vigorous aeration immediately after loading the barley into the steep tank also serves to raise dust, chaff and light grains to the surface for removal. These are accumulated and sold for livestock feed.

Aeration, damping and temperature must all be carefully controlled to ensure that germination occurs at the required rate and to the required degree. For poorly modified traditional pale lager, European two-rowed barley needs steeping to 41%–43% m.c., while for a pale ale malt of 43%–45% m.c. is appropriate. For a high-nitrogen barley (say 1.8% N) destined for a vinegar factory, 46%–49% m.c. may be preferred. Higher moisture levels induce faster modifications in the barley but greater losses are incurred (Briggs, 1978). Anaerobic conditions are dangerous, as they favour fermentation by the microorganisms present and the alcohols produced can harm the grain. On the other hand, excessive aeration leads to 'chitting' under water and, consequently, an unwanted rise in moisture content.

It is desirable to replace the steeping water with fresh water for a given batch of grain (between one and four times), as phosphates and organic compounds, including alcohols, accumulate and the microbial population grows. During the first steep, dissolved oxygen is depleted from steep

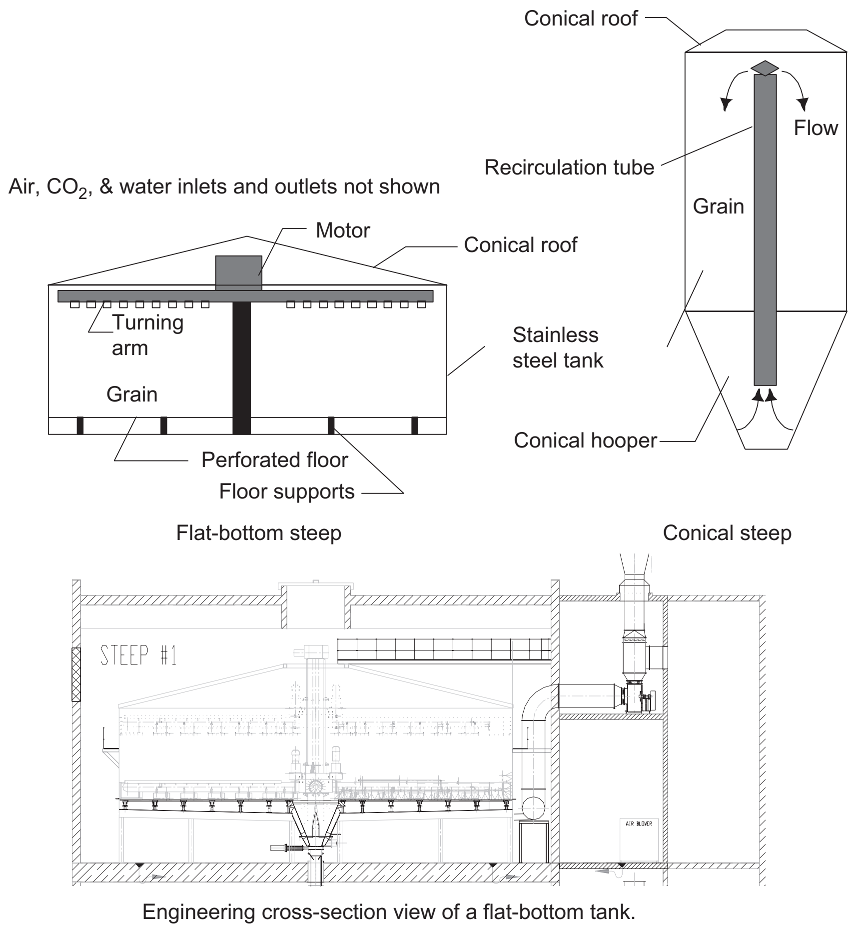


FIGURE 12.8 Typical steeping vessels. *Adapted from Williams, G.D., Rosentrater, K.A., 2005. Design Considerations for the Construction and Operation of Malting Facilities. Part 1: Planning, Structural, and Life Safety Considerations. Paper 054095. Annual Meeting of the American Society of Agricultural and Biological Engineers, Tampa, FL, USA.*

water at a rate of ~1 ppm/h, but this rate of depletion rises tenfold by the third steep (complete depletion is possible within 1 h). Temperature is controlled to a degree by the water temperature to between 10 and 16°C.

There are many variations in steeping practice, including steeping in running water ('Bavarian') or the 'flushing' regime, in which immersions are frequent but cover the grains for only a few minutes. Modern steep tanks are filled with barley to a depth of about 1.2 m. This increases to approximately 1.8 m when the grain is swollen. The uniform depth of flat-bottomed tanks provides for more uniform aeration and CO_2 removal than in conical-bottomed vessels.

Following steeping, the grain is transferred to germinating vessels. This may be by 'wet-casting', whereby it is pumped in water suspension, or by 'dry-casting' (mechanical conveyor) after draining. If additives are to be used it is convenient to add them during transfer. They may include gibberellic acid (https://en.wikipedia.org/wiki/Gibberellic_acid) or potassium bromate (https://en.wikipedia.org/wiki/Potassium_bromate). The former hastens malting, especially if bruised grains are present, while potassium bromate reduces respiration and hence the rise in temperature that accompanies it. It is also said to inhibit proteolysis and control colour development in the malting grain, as well as to reduce malting loss by reducing root growth.

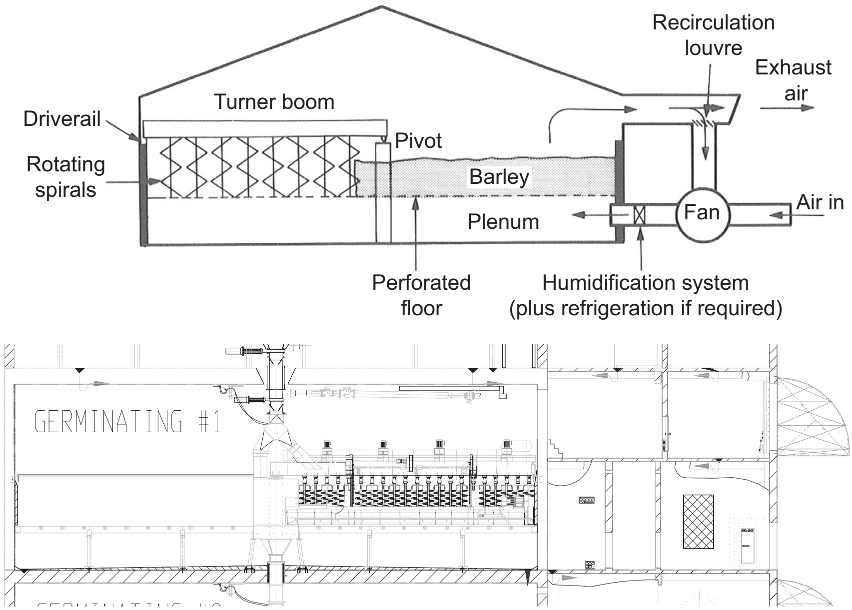
12.2.4 Germination

Early mechanical maltings had rectangular germination vessels; this method was supplanted by the drum, which provided ideal control but was limited to about 100 tonnes capacity and had a high unit cost. Later, circular germination vessels were developed and capacities rose to 500 tonnes or more. Features common to all mechanical germination vessels are an automatic means of turning the germinating grains and a means of aeration. Turning may be performed by rotating spirals or augers that are moved slowly through the grain mass. In the rectangular vessels they move end to end on booms, while in the circular type vertical turners rotate on a boom, or alternatively remain stationary while the grain is transported past on a rotating floor. It is common for aeration to be provided by air passing up (usually) or down, from or into a 'plenum' beneath the floor, which is constructed of slotted steel plates.

The layout of a typical circular germination vessel is shown in Fig. 12.9. Fig. 12.10 illustrates two variants of malting towers; each has separate levels for steeping and germinating.

Temperature and humidity are controlled by humidifying and refrigerating or warming the air which passes through the grain mass. Air volumes passing are of the order of 0.15–0.2 m^3/s/tonne of barley. Temperatures of 15–19°C are common. Microprocessor control of conditions is commonplace (Gibson, 1989).

In these types of systems the danger of microbial contamination is high, as air passing with high humidity is ideal for growth of bacteria and fungi, and nutrients are plentiful. As well as introducing health hazards and off-flavours, microbes gain preferential access to oxygen, thus potentially inhibiting the germination and modification of the barley for which the system is designed. In some plants the germination and kilning are carried out in a single vessel, and this has the advantage of the microbes being killed by the heat of kilning. Cleaning the dry residue is easier than complete removal of the wet remains of germinating grain.



Engineering cross-section view of a germination system.

FIGURE 12.9 Typical circular germination vessel. *Based, in part, upon Williams, G.D., Rosentrater, K.A., 2005. Design Considerations for the Construction and Operation of Malting Facilities. Part 1: Planning, Structural, and Life Safety Considerations. Paper 054095. Annual Meeting of the American Society of Agricultural and Biological Engineers, Tampa, FL, USA.*

12.2.5 Kilning

The objectives of kilning are to arrest botanical growth and internal modification of the barley, to reduce moisture for grain storage and to develop colour and flavour compounds in the malt. Kilning is responsible for 90% of the energy consumption of the entire malting process unless a heat recovery unit is in use, when the proportion may be reduced to ~75%–80%.

For kilning, ambient air is heated by combustion of fuel (most often natural gas) and passed under positive or negative pressure through the bed of grains. A plenum below the floor is used, as in the earlier stages of the malting process. A recent innovation in kiln design is the multideck kiln. In this system green malt is loaded on to the upper decks and progressively transferred to the lower decks after partial drying. Warmed air is passed first through the drier, lower beds before passing, unsaturated, to the upper beds where it is capable of removing moisture from the green malt (Fig. 12.11).

The depth of green malt in a modern kiln is ~0.85–1.2 m. For maximum efficiency the bed should be level and uniformly compacted, a condition readily achieved by the automatic or semiautomatic loading machinery available today.

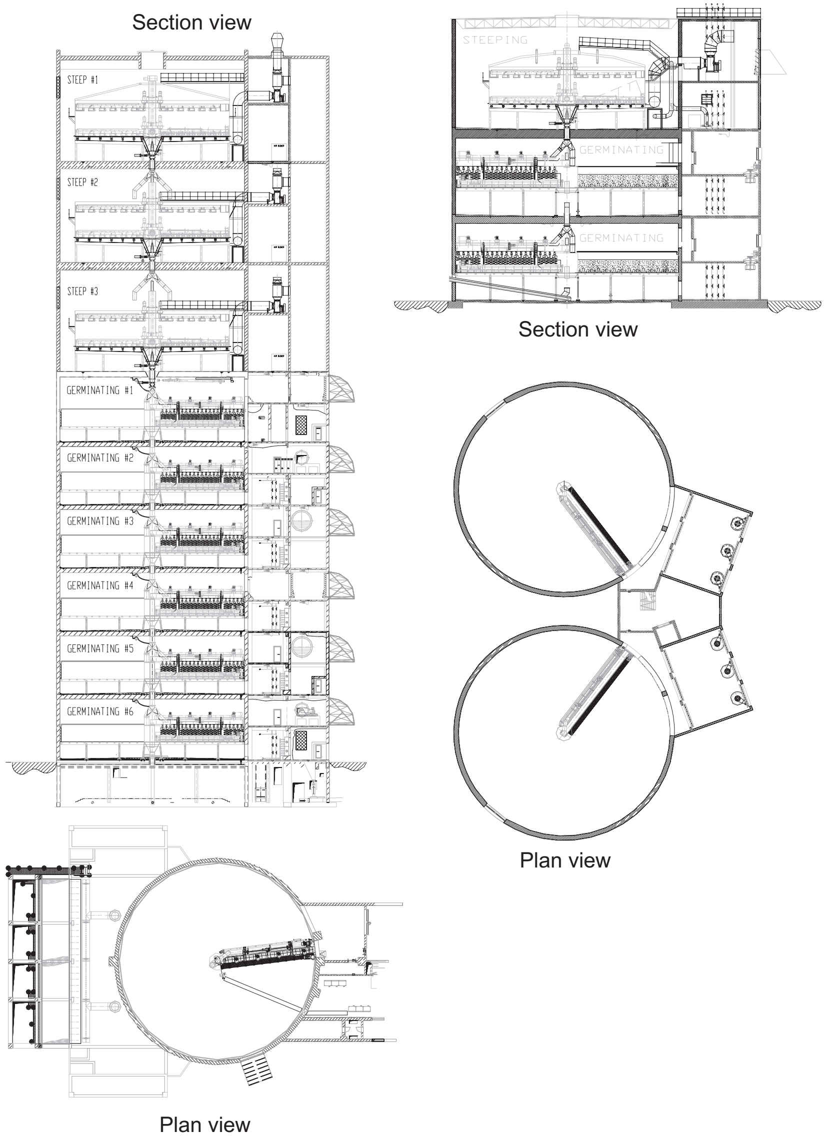
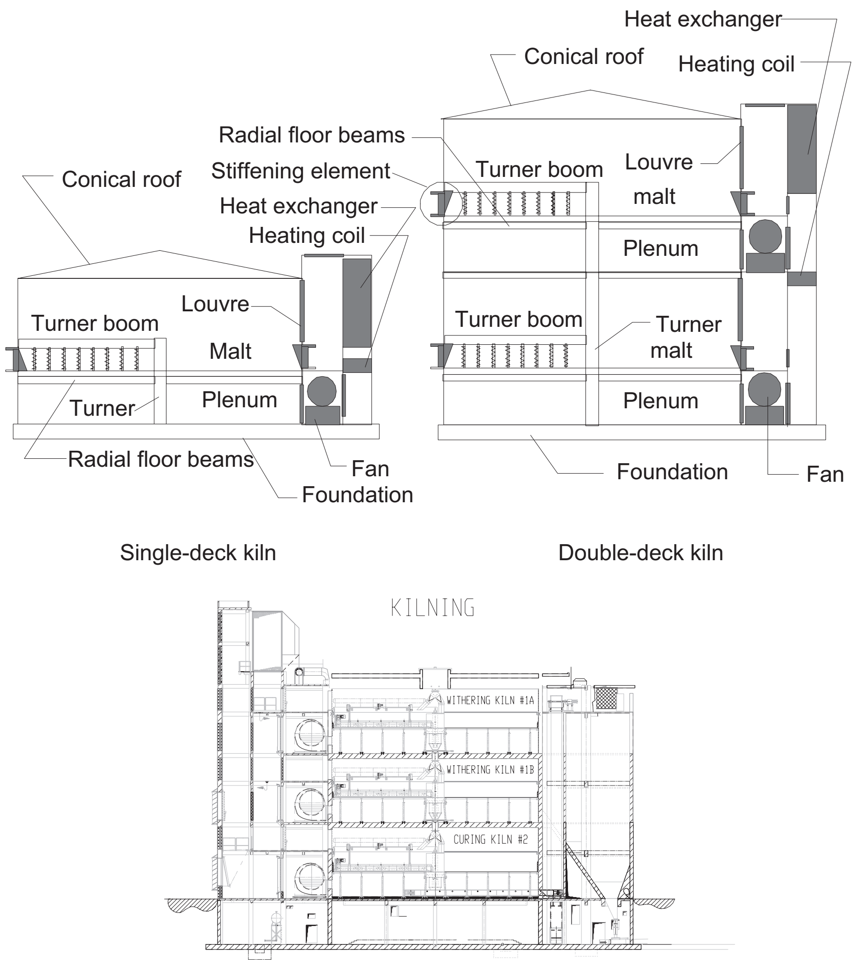


FIGURE 12.10 Engineering views of malting towers. Left: three steep levels and six germinating levels. Right: one steep level and two germinating levels.

Conditions for kilning are determined by the nature of the end product required. Variables include the extract potential, moisture content, colour, flavour profile and enzyme activity. Curing temperatures range from 80 to 100°C. In modern kilns the maltster is assisted in monitoring and controlling conditions by computerized control programs incorporated into automated systems.



Engineering cross-section view of a three-deck kiln.

FIGURE 12.11 Typical single-deck and multideck kilns. *Adapted from Williams, G.D., Rosentrater, K.A., 2005. Design Considerations for the Construction and Operation of Malting Facilities. Part 1: Planning, Structural, and Life Safety Considerations. Paper 054095. Annual Meeting of the American Society of Agricultural and Biological Engineers, Tampa, FL, USA.*

Enzymes survive high curing temperatures best if the malt is relatively dry, but under these conditions colour and flavour development are minimal. They develop mainly as a result of Maillard reactions occurring between the reducing groups of sugars and amino groups. Development of additional flavour compounds is favoured by the combination of high temperatures with wet malts (Briggs, 1978). Other factors affecting malt colour may be added caramelized sugars and oxidized polyphenols, and other contributions come from aldehydes, ketones, alcohols, amines and miscellaneous other substances, including sulphur-containing compounds and nitrogenous bases. These are discussed in detail by Briggs (1978) and Palmer (1989).

Peated distillery malts for Scotch whisky manufacture take up many substances from peat smoke and contain various alkanes, alkenes, aldehydes, alcohols, esters, fatty acids and aromatic and phenolic substances, including phenol and cresols. The use of peat as a fuel for kilning originated in cottage-industry enterprises in the crofts of the Scottish Highlands where peat was the only available fuel for domestic heating. In lowland distilleries peat heating has now been superseded by a succession of fuels, most often natural gas. Direct heating by these fuels is not permitted, though, as they can lead to introduction of nitrosamines and other deleterious chemicals into the product. Peatiness is a valued character of malt whiskies, and direct heating with peat is the rule in their production.

For production of brewing malts a major economic consideration is brewers' extract. This is measured as hot water extract available as the soluble nitrogen required to maintain fermentation and beer quality properties. An analysis of ale malt compared with that of barley is shown in Table 12.2. The characteristics of brewers' malts of various types are given in Table 12.3, and some are illustrated in Fig. 12.12.

TABLE 12.2 Analytical characteristics of barley and ale malt

Constituent	**Barley**	**Ale malt**
Moisture content (%)	15	4
Starch (%)	65	60
β-ᴅ-glucan	3.5	0.5
Pentosans (%)	9.0	10.0
Lipid (%)	3.5	3.1
Total nitrogen (%)	1.6	1.5
Total soluble nitrogen (%)	0.3	0.7
α-Amino nitrogen (%)	0.05	0.17
Sucrose (%)	1.0	2.0
Minerals (%)	approx. 2	approx. 2
Colour (°EBC)	<1.5	5.0
Hot water extract (1°/kg)	150	305
Diastatic power (*beta*-amylase °L)	20	65
Dextrinizing unit (*alpha*-amylase)	<5	30
Endo β-glucanase (IRV units)	<100	500

Based upon data from Palmer, G.H., 1989. Cereals in malting and brewing (Chapter 3). In: Palmer, G.H. (Ed.), Cereal Science and Technology. Aberdeen Univ. Press, UK. Reproduced by courtesy of Aberdeen University Press.

TABLE 12.3 Characteristics of a selection of malts

Malt type	Extract (°/kg)	Moisture (%)	Colour (°EBC)	Final kilning temperature (°C)
Ale[a]	305	4.0	5.0	100
Lager[a]	300	4.5	2.0	80
Cara Pils	265	7.0	25–35	75
Crystal malt	268	4.0	100–300	75
Amber malt	280	2.0	70–80	150
Chocolate malt	268	1.5	900–1200	220
Roasted malt	265	1.5	1250–1500	230
Roasted barley	270	1.5	1000–1550	230

[a] *Of all the malts listed only ale and lager malts contain enzymes.*
Based upon data from Palmer, G.H., 1989. Cereals in malting and brewing (Chapter 3). In: Palmer, G.H. (Ed.), Cereal Science and Technology. Aberdeen Univ. Press, UK. Reproduced by courtesy of Aberdeen University Press.

12.2.6 Ageing

Before use it is necessary to mill the kilned malt, but it is customary to delay this process to permit moisture equilibration. Kilning results in rapid drying of the bulk grain, but in individual grains a gradient will actually exist, from a higher inner to a lower outer (husk) moisture content. Differences in a malt of 3%–5% m.c. may actually be 4 or 5 percentage points (1%–3% m.c. outside to 5%–8% m.c. inside). Unless equilibrated, agglomeration of the damper parts can reduce extraction potential and undue fragmentation of dry husk can lead to haze in the extract (Pyler and Thomas, 1986). Storage for up to 3 months may be used. As specifications become increasingly sensitive to moisture content, the conditions of storage progressively include humidity control (Palmer, 1989).

12.2.7 Energy consumption and other costs

The Energy Technology Support Unit published a report in 1985 of a survey of British maltsters. Specific energy consumed per tonne of malt ranged from 2.48 to 6.81 GJ, with a weighted average of 3.74 GJ. Quoted costs included fuel and electricity, and power costs encompassed grain handling and process requirements. Additional estimates include 1058–1534 kWh/tonne for total energy consumption, 900–1200 kWh/tonne for heating air in the kiln, 25–75 kWh/tonne for air movement in the kiln and 27–44 kWh/tonne for steeping and germination (Briggs, 1998).

FIGURE 12.12 Examples of various malts.

Estimates of proportionate costs, including these values, are given by Gibson (1989) as:

Fuel 25%–30%
Electricity 15%–20%
Wages 15%–20%
Repairs/maintenance 10%–20%
Miscellaneous 15%–25%

As with many wet cereals processes, the costs of water treatment before discharge are increasing as environmental standards become more stringent. The biological oxygen demand (BOD) load from a 30,000 tonnes per annum malting is equivalent to a population of about 9000 persons (Gibson, 1989). It has been estimated that 44 million m^3 water is used per annum for malting, which results in 30 million m^3 of wastewater (http://www.ukmalt.com/water).

12.2.8 Malt production

Palmer (1989) reported that about 17 million tonnes of barley was used worldwide in 1989 to produce 12 million tonnes of malt and about 970 million hL of beer. This represented about 10% of world barley production. In 2015 global malt production was reported to be nearly 23 million tonnes, of which approximately 9.7 million tonnes came from Europe (Euromalt, 2017).

12.2.9 By-products of malting

The main by-product of malting is called ‘malt sprouts’ or ‘culms’ (Fig. 12.13). They are separated from the kilned malt by passing the malt through revolving reels or a wire screen. They account for 3%–5% of product and are incorporated into livestock feeds. Typically they contain 25%–34% N compounds, 1.6%–2.2% fat, 8.6%–11.9% fibre, 6.0%–7.1% ash and 35%–44% N-free extract (Pomeranz, 1987). More information is available from the Maltsters’ Association of Great Britain (http://www.ukmalt.com/malting-co-products) and Feedipedia (www.feedipedia.org).

12.2.10 Nonbrewing uses of malt

Milled barley malt is used as a high-diastatic (i.e., amylolytic) supplement for bread flours, which are low in natural diastatic activity, and as a flavour supplement in malt loaves. Malt extracts and syrups are produced by concentrating worts by evaporation. Malt is also used in the manufacture of malt vinegar, drink products such as Ovaltine, candy and confectionery products such as Whoppers and Malted Milk

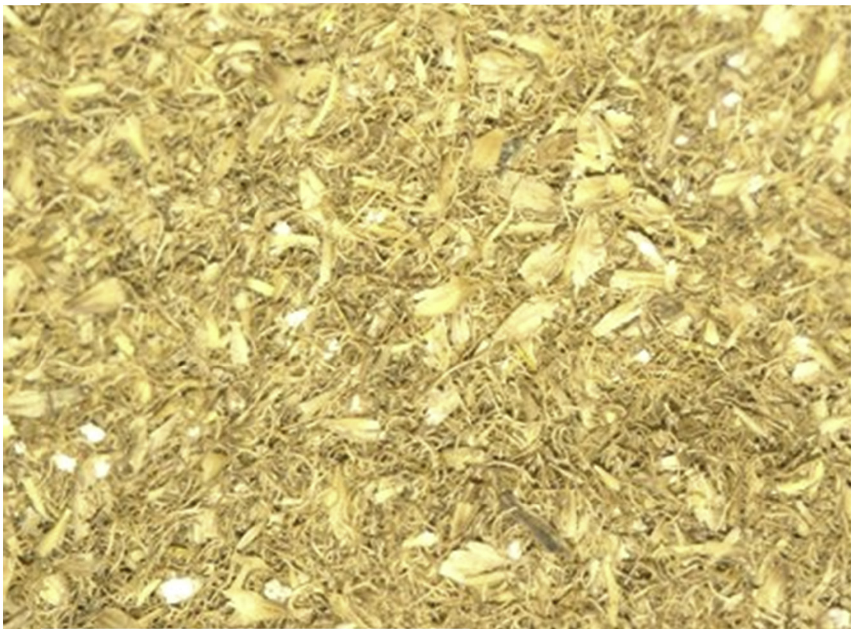


FIGURE 12.13 Malt sprouts which have been separated from the malt are used for cattle feed because of their protein and fibre levels.

Balls, and foods such as bagels, breads and breakfast cereals. Malt and malt extract have also been used as sweeteners in food products (www.maltproducts.com).

12.2.11 Adjuncts

Although malt derived from barley is generally considered to be the superior feedstock for brewing and distilling, it is common practice in many countries to supplement malt with alternative/additional sources of soluble sugars or starch capable of conversion to soluble sugars.

The principal adjuncts, as such nonmalt additives are termed, are rice, maize grits and cereal starches. Adjuncts contribute virtually no enzymes to the wort, so hydrolysis of their starch depends upon the enzymes present in the malt to which they are added. Use of adjuncts is common practice in the United States, and this is one reason for the preference there for the higher-enzyme-containing six-row barleys.

It has been estimated that in the United States 38% of total materials used in brewing (excluding hops) were adjuncts (Pyler and Thomas, 1986). Of these, 46.5% was corn grits, 31.4% rice and 0.7% barley. Sugars and syrups accounted for the remaining 21.4%.

The form in which rice is added is typically broken grains that do not meet the requirements for milled rice. As the quality of the products of fermentation is little affected by the physical nature of the adjunct (if preserved appropriately), the choice is usually made purely on economic grounds. This is not related only to the price per tonne of the adjunct, though, because the yield of extract is not the same from each. Tests for extraction carried out in the laboratory generally give higher values than those obtained in commercial practice. For example, Pyler and Thomas quote 78% for rice and 74% for maize grits in the brewhouse, but 87%–94% and 85%–90%, respectively, in the laboratory (American Society of Brewing Chemists procedure). Maize grits also contain higher levels of fat and protein than rice – constituents, which are considered undesirable.

Other adjuncts commonly used are refined maize starch, wheat and wheat starch, rye, oats, potatoes, tapioca, triticale, heat-treated (torrefied or micronized) cereals and cereal flakes. Micronization involves heating grains to nearly 200°C by infrared radiation, while torrefication achieves similar temperatures by use of hot air (Palmer, 1989). In grains treated by either method the vaporized water produced disrupts the physical structure of the endosperm, denaturing protein and partially gelatinizing starch. Digestibility is thus increased, and these products are also used in cattle feeds and whole-grain baked products. Solubility of proteins may be decreased and some flavours may be introduced through their use if adequate treatment temperatures are used in processing. Heat-treated cereals can be added to malt before grinding; their extract yield is increased if they are precooked before use. Investigations with extruded cereals gave poorer extract yields than traditional adjuncts, however (Briggs et al., 1986).

Sorghum was used considerably in the United States when maize was in short supply during World War II, while today it is used to a significant extent in Mexico and parts of Africa (examples include *bil-bil* in Cameroon, *burukutu* in Nigeria, *pombe* in East Africa and *bjala bja setso* in northern Sotho). Sorghum has lower fat and protein contents but a higher extract than maize, so it has some merit as a substrate. Moreover, it has seen a resurgence in the United States in recent years due to development of gluten-free beers (see, for example, http://www.bardsbeer.com, http://www.redbridgebeer.com).

Barley and wheat starch have lower gelatinization temperatures than maize and rice starch, hence digestion may occur at mash temperatures. It is usual, however, to premash maize, rice, wheat, barley, etc. by cooking with a small amount of malt before adding them to the mash.

Addition of barley provides a means of reducing the nitrogen content of the wort. It is disallowed, however, by the German beer law for the production of bottom-fermented beers, in which only barley malt, hops, yeast and water are allowed. Top-fermented beers follow the same regulations

TABLE 12.4 Beers made from wheat malt and their characteristics

Type	Character	Origin	Alcohol (% v/v)	Flavour features
Weizenbeer	Lager/ale	Bavaria	5–6	Full-bodied, low hops
Weisse	Lager	Berlin	2.5–3	Light flavoured
Gueuze-Lambic	Acid ale	Brussels	5+	Acidic
Hoegards wit	Ale	East of Brussels	5	Full-bodied, bitter

Based upon data from Pomeranz, Y., 1987. Barley (Chapter 18). In: Pomeranz, Y., (Ed.), Modern Cereal Science and Technology. UCH Publishers Inc., NY, USA, using information from Leach, A.A. of the Brewers' Society, UK.

but wheat malt may be included (Narziss, 1984). For special beers, pure beet-cane-invert sugar is allowed.

12.2.12 Malts from other cereals

In Africa many malts are produced from sorghum and, to a lesser extent, millets and other cereals (e.g., teff). It has been reported that in the Republic of South Africa commercial production using sorghum may be in the order of 1×10^9 L annually, and home brewing may be in the same order (Novellie, 1977).

Wheat malt is used in the production of wheat malt beers. Examples of these and their characteristics are shown in Table 12.4.

Malts made on a pilot scale from triticales grown in the United Kingdom were evaluated by Blanchflower and Briggs (1991). Viscosities of resulting worts were high due to pentosans, particularly arabinose and xylose. Hot water extracts after 5 days germination were 302–324 L°/kg. Filtered worts were turbid owing to proteinaceous materials. Malt yields were between 87% and 90%.

12.3 BREWING

12.3.1 Beer

The overall brewing process is summarized schematically in Fig. 12.14.

12.3.2 Wort production

The starting material for brewing may be pure (usually barley) malt or a mixture of malt and adjuncts. If solid adjuncts are to be included they

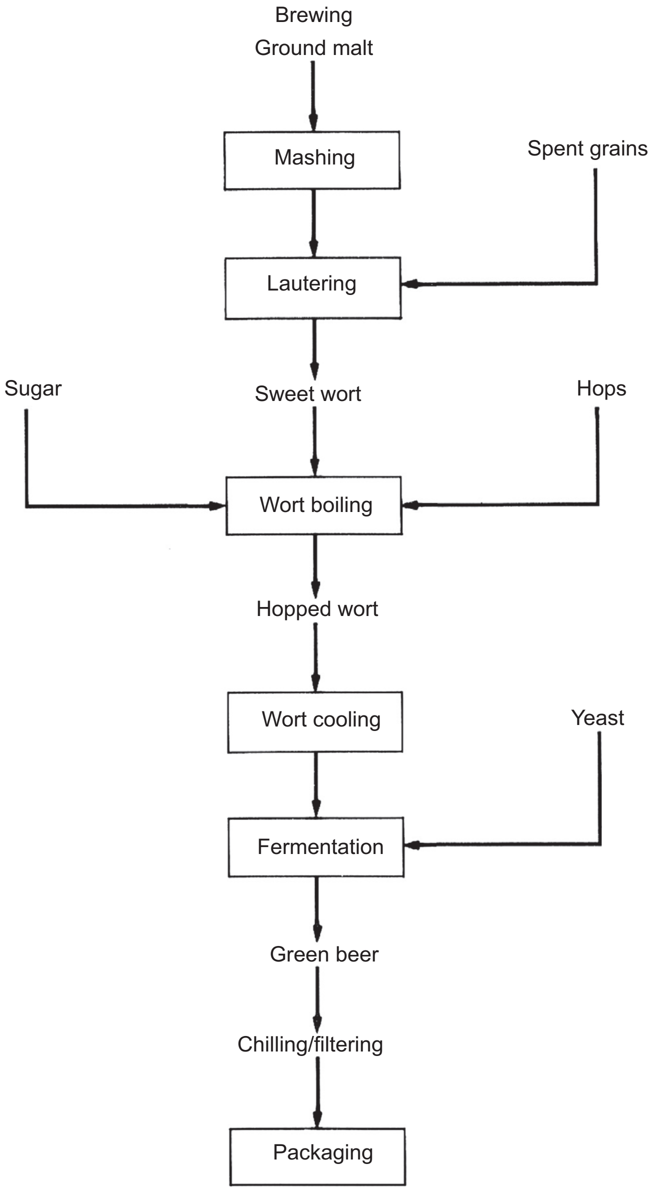


FIGURE 12.14 Flow chart summarizing the major steps in the brewing process.

may be milled with the malt. The coarsely ground material, upon hydration with brewing liquor (i.e., water, salts, sugars, syrups, etc.), produces a brewers' extract from the soluble materials in the malt and a filter bed from the husk. The quality of the filter bed depends on the size of the husk particles; they should not be too fine. The process is known as 'mashing' and is carried out in vessels called mash tuns.

After an initial rest for hydration, the temperature is raised above the gelatinization temperature of the starch. This renders the starch much more susceptible to digestion by amylase enzymes, to produce soluble sugars. The process of conversion, begun during malting, thus continues during this phase.

It is now necessary to separate the liquid wort from the solid remains of the malt and adjuncts, which is done by a process called 'lautering'. The spent grains (known as brewers grains and discussed in more depth later in this chapter) act as a filter bed when the mixture is transferred to a lauter tub (tun), which has a perforated/screened bottom. The spent grains accumulate on this and allow the liquid to pass through while retaining the solids. The sugary liquid is known as the 'sweet wort'; it may be supplemented with syrups, sugars, caramel, etc. at this stage if such adjuncts are to be used to increase the amount of fermentable sugars for fermentation. Hops are also added at this stage. As well as adding flavour they serve to sterilize the wort (hop acids have antimicrobial properties) and participate in reactions that precipitate proteins responsible for haze when the wort is boiled.

The sweet wort is placed in another tank, and the temperature is raised to boiling. Boiling may continue for 1.5–2.0 h. During boiling the humulones, or alpha-acids, are isomerized to the bitter iso-alpha-acids, enzymes are inactivated and contaminating bacteria are sterilized. Because the yield of bitter iso-alpha-acids extracted from the hops by boiling may be as low as 30%, a modern procedure is to replace part of the raw hops by a preisomerized hop extract, which is added to the beer after fermentation. It is common for half the hops to be added at the beginning of the period and half at the end. The wort is cooled (to 15.5–18°C for ales and 4–7°C for pilsners and lagers), filtered, then transferred to pitching tanks where it is 'pitched' with yeast (i.e., yeast is added). Air is also passed into the hopped wort (aeration) to provide a supply of oxygen for the yeast, which rapidly becomes active (added oxygen reduces the lag phase that would otherwise occur). Further information is provided in Briggs (1998).

12.3.3 Fermentation

Yeasts vary in their behaviour during fermentation: some strains tend to flocculate, and as a result they trap CO_2 and rise to the top. Others, which do not flocculate, sink to the bottom. Several styles of lagers are produced by bottom fermentation, while many types of ales and stouts are produced using top fermentation. Some examples of common beers are provided in Table 12.5.

TABLE 12.5 Classical beers of the world classified according to yeast types used in their brewing

Type	Character	Origin	Alcohol (% v/v)	Flavour features
BOTTOM-FERMENTED				
Münchener	Lager/ale	Munich	4–4.8	Malty, dry, moderately bitter
Vienna (Märzen)	Lager	Vienna	5.5	Full-bodied, hoppy
Pilsner	Lager	Pilsen	4.5–5	Full-bodied, hoppy
Dortmunder	Lager	Dortmund	5+	Light hops, dry, estery
Bock	Lager	Bavaria, United States, Canada	6	Full-bodied
Dopplebock	Lager/ale	Bavaria	7–13	Full-bodied, estery, winey
Light beers	Lager	U.S.	4.2–5	Light-bodied, light hops
TOP-FERMENTED				
Saissons	Ale	Belgium, France	5	Light, hoppy, estery
Trappiste	Ale	Belgian and Dutch abbeys	6–8	Full-bodied, estery
Kölsch	Ale	Cologne	4.4	Light, estery, hoppy
Alt	Ale	Düsseldorf	4	Estery, bitter
Provisie	Ale	Belgium	6	Sweet, ale-like
Ales	Ale	United Kingdom, United States, Canada, Australia	2.5–5	Hoppy, estery, bitter
Strong/old ale	Ale	United Kingdom	6–8.4	Estery, heavy, hoppy
Barley wine	Ale/wine	United Kingdom	8–12	Rich, full, estery
Stout (bitter)	Stout	Ireland	4–7	Dry, bitter
Stout (Mackeson)	Stout	United Kingdom	3.7–4	Sweet, mild, lactic, sour
Porter	Stout	London, United States, Canada	5–7.5	Very malty, rich

Based upon data from Pomeranz, Y., 1987. Barley (Chapter 18). In: Pomeranz, Y., (Ed.), Modern Cereal Science and Technology. UCH Publishers Inc., NY, USA, using information from Leach, A.A. of the Brewers' Society, UK.

A typical type of fermenter is a deep cylindrical vessel with a conical base (Fig. 12.15) into which the yeast eventually sediments (which eases cleaning and sterilization of the equipment after fermentation is complete) – flat-bottomed tanks present draining, cleaning and sanitation challenges.

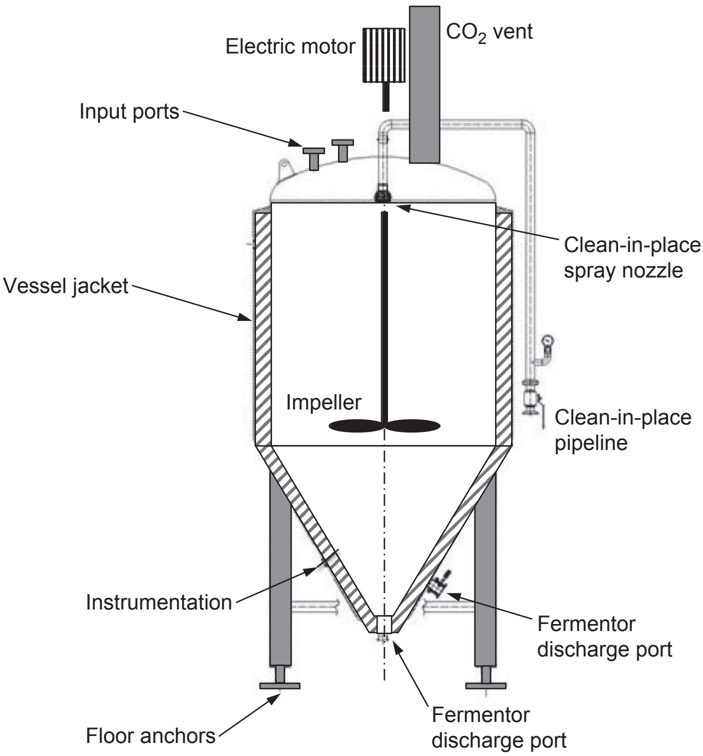


FIGURE 12.15 Conical bottom fermentation vessel.

In fermentation vessels the liberation of carbon dioxide can provide agitation, but in some cases sparging or impellers may also be used to increase agitation, which prevents the glucose substrate from becoming rate-limiting to the fermentation reactions. Accounting for the filling, fermentation, emptying and cleaning to be accomplished, a complete cycle time of approximately 5 days at 12°C or 2.5 days at 18°C is common.

As long as a substrate is available, fermentation could continue for 7–9 days, producing ethanol and carbon dioxide (in approximately equal proportions). The gas may then be collected for sale or adding back when the beer is bottled or casked, or it may be released to the atmosphere. The fermentation reaction is exothermic and the temperature would rise unduly if not controlled by heat exchangers or jackets surrounding the fermentation vessel. The yeast cell mass also increases during fermentation through asexual reproduction, and this constitutes an additional by-product. During fermentation the pH drops from ~5.2 to ~4.2 as a result of acetic and lactic acids synthesized by contaminating bacteria inevitably introduced with the yeast during the process. The green (jargon for young) beer is separated from the aggregated yeast cells and cooled to precipitate further haze-producing proteins, and then aged before filtering and carbonating. Lagers are stored at ~0°C for some weeks ('lagering') before packaging into bottles or kegs. The beer may also be pasteurized. An alternative treatment is for the green beer to be placed into casks, primed with sugars to permit secondary fermentation and 'fined' (or clarified) by including isinglass (a collagen from fish), which coagulates with the yeast for ready separation from the beer – this is then sold as 'naturally conditioned' beer, a product peculiar to the British Isles. Some common beers are listed in Table 12.5. Further information is provided in Briggs (1998).

Further technical details about malting and brewing are given in Bamforth (2006). Some of the latest developments in the brewing of beers can be found in Lewis and Young (2013).

12.3.4 Saké

Saké production was reported to be 15×10^5 kL in 1985; of this 10×10^5 kL (or ~ 2/3) were produced in Japan. In 2009 approximately 1.7×10^6 kL were consumed, but its popularity among 20-year-olds was only 1/2–1/4 that of older age groups (Kanauchi, 2013).

An essential difference between beer and saké is that for saké the natural enzymes present in the grain are not employed in solubilizing the starch – indeed, they are expressly deactivated before the saccharifying phase of saké brewing. Enzymes are of course needed, and these are derived from the fungus *Aspergillus oryzae*; they are provided from a culture of that mould known as 'koji', in which the microorganism is added to steamed rice and incubated. Koji contains 50 different enzymes, including the *alpha*- and *beta*-amylases present in malt, and an additional amylolytic enzyme, glucoamylase, capable of hydrolysing starch polymers to glucose. The balance of amylase to protease is influenced by cultural conditions, with higher temperatures favouring amylase production. The saké production process is summarized in Fig. 12.16 and more information about the process can be found at http://www.japansake.or.jp/sake/english/sake-basics/process.html.

The yeast used in saké production is a specialized strain of *Saccharomyces cerevisiae*.

Unlike the husk of barley in the malting process, rice husk is not valued for its filtration properties, nor indeed any other qualities. It is removed by milling. The degree of polishing is severe, typically removing 25%–30% of the brown rice weight, and in extreme cases up to 50%. Following milling the rice is washed, steeped and steamed for 30–60 min. For 1 tonne of rice approximately 25 kg of water is used during processing (Yoshizawa and Kishi, 1985).

Koji is added to the main mash in a seed mash: steamed rice in which an inoculum of *A. oryzae* has been cultured. Steamed rice and seed mash are added in equal proportions, and water and saké yeast are also added. Quantities involved in a mash are usually 2–7 tonnes,

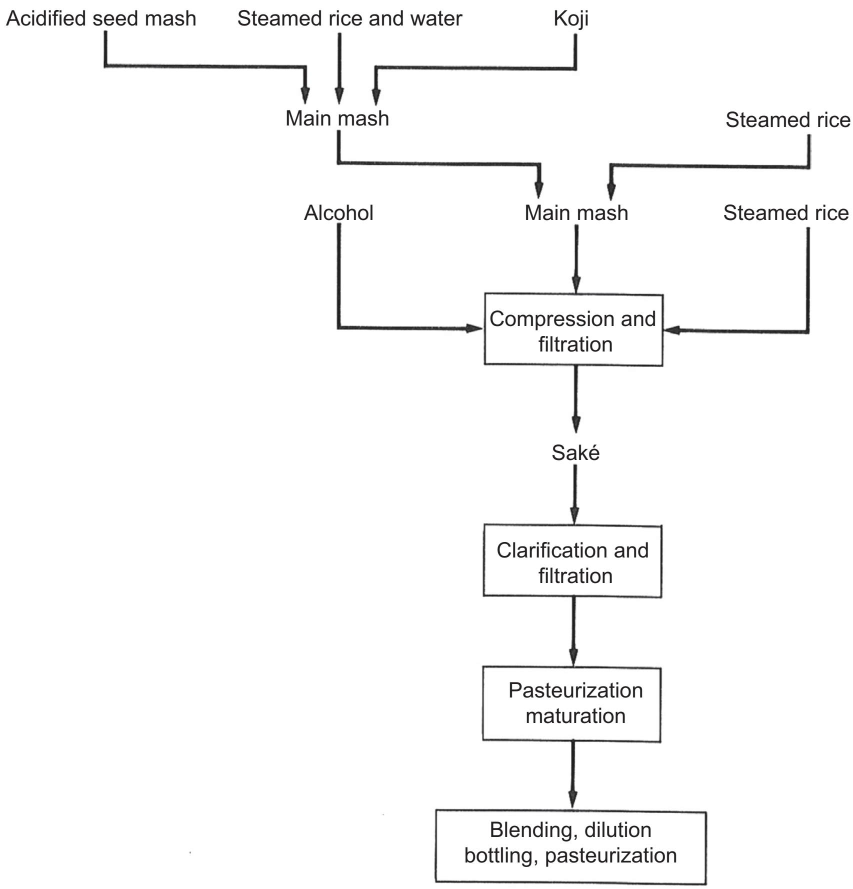


FIGURE 12.16 Flow chart summarizing the major steps in saké production.

but over 10 tonnes is possible. The seed mash is acidic as a result either of lactic acid bacteria present or of added lactic acid. The acid conditions inhibit wild microorganisms. After 2 days at 12°C the yeast population reaches the high concentration originally present in the seed mash (10^8 cells/g) and an equal amount of steamed rice and water are again added. A third addition is made the following day and fermentation increases in vigour, raising the temperature from about 9°C to 15–18°C. By 15–20 days after the final addition the alcohol content rises to 17%–19% and fermentation virtually ceases. The high alcohol content is attributable to four factors.

1. The tolerance of the yeast.
2. The low sugar content of the mass at any time.
3. The solid matrix of the mash.
4. The proteolipids in koji.

The alcohol content of the liquid is further increased to 20% before filtration and pasteurization of the saké. Maturation takes 3–8 months, after which water is added to give 15%–16% alcohol content. Bottling takes place after filtration through activated carbon to improve colour and flavour.

The by-products from the process, liquid lees and solid cake (*kasu*), are typically packaged and sold as human food products. On average, 1 tonne of rice will yield 3 kL of sake and 200 kg of *kasu* (Kanauchi, 2013).

12.4 DISTILLED SPIRITS

Distillation is a process of evaporation and recondensation used to separate liquids into various fractions according to their boiling temperature ranges. In the context of beverages it is used to produce potable spirits with an alcohol content above that of fermented drinks.

Spirits produced from grains are of two major categories, whisky (or whiskey, according to its origin – whisky is only produced in Scotland!) and neutral spirits. In whiskies care is taken to retain flavours and colours carefully introduced during production (i.e., produce character), while in neutral spirits the goal is to avoid introduction of flavours and colours during production, although flavours may be added later, for example in gin.

Whiskies of several types exist, their names denoting the carbohydrate source from which they are derived, the manner of their production and sometimes their origin. The essential characteristics of some are briefly described below. Standards of identity in the United States are provided in 27 CFR 5.22.

Scotch malt whisky is produced by traditional methods, using malt as the sole carbohydrate source (by legal definition – http://www.legislation.gov.uk/uksi/2009/2890/contents/made).

Grain whiskey is made from a mash of cooked grain and saccharified by the action of enzymes from malted barley. The grain may be maize, barley, wheat or others.

In Bourbon whiskey the grain in the mash consists of at least 51% (and usually 60%–70%) maize. Typically some rye is included to impart a spicy, estery flavour. Although included, malt contributes only 10%–15% of total carbohydrate.

Rye whiskey contains at least 51% of rye grain. Irish whiskey is made predominately from malted or unmalted barley. For both of these, wheat, rye or oats make up the remainder. Canadian whiskies are mainly blends of neutral grain whiskies (~90%) and Bourbon or rye whiskeys (Nagodawithana, 1986).

Figs 12.17(a) and (b) AB show some examples of a typical whisky/whiskey distillery.

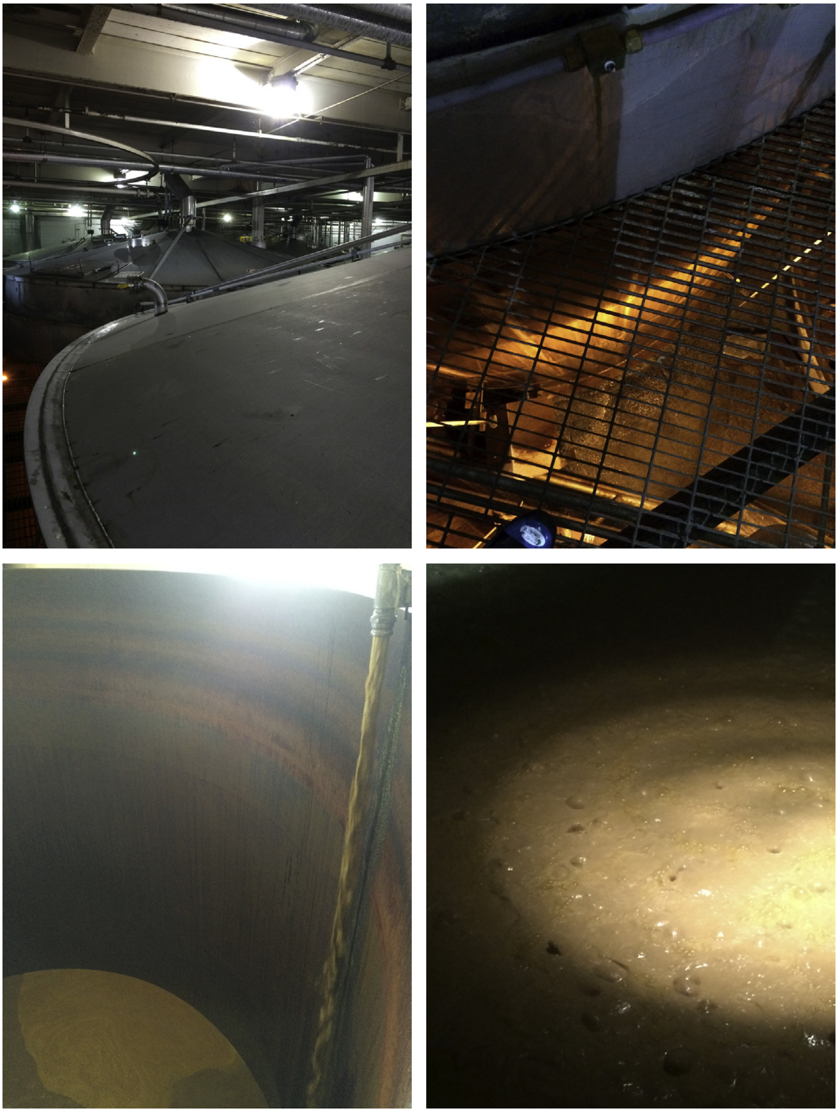


FIGURE 12.17A Grain whiskey fermentation, showing top of the fermentor vessel (including ports for inspection, ingredient addition and CO_2 off-gassing), water cooling on the outside of the vessel for temperature control during fermentation, filling the fermentor with water and mash and CO_2 bubbles during active fermentation.

12.4.1 Traditional malt whisky (Scotch)

The traditional whisky-making process is summarized in Fig. 12.18. Well-modified peated malt is dried at relatively low temperatures (to retain enzyme activity), milled and mashed at temperatures of 64–65°C.

FIGURE 12.17B Barrel storage warehouse.

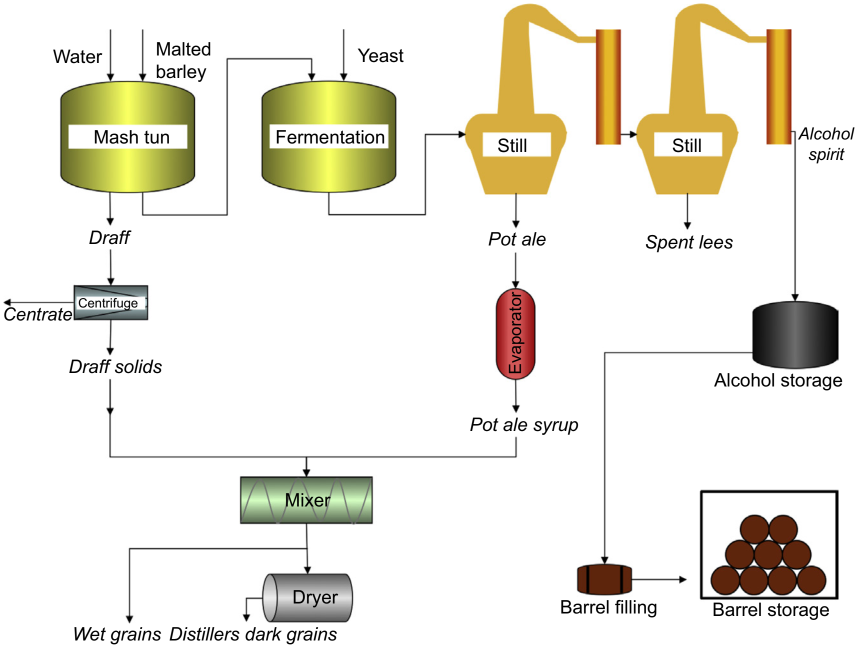


FIGURE 12.18 Flow chart summarizing the major steps in Scotch whisky production.

The first worts are run off before mashing at a higher temperature of 70°C and running off a second wort. Both worts become the liquor that is fermented. Two further worts are produced from mashes at 80 and 90°C, and are used as mashing liquor for subsequent grists. Batches of 5–10 tonnes of malt are typical.

Fermentation is preceded by cooling to 20–21°C, and is initiated by pitching with yeast. Yeasts are of the high-attenuation type (tolerating high alcohol levels) grown in molasses and ammonium salts. They are also selected to produce appropriate flavours. After 36–48 h, alcohol content reaches 8% and the temperature reaches 30°C due to heat produced during yeast metabolism.

The contents of the fermenter are transferred to the first copper pot still (Fig. 12.19; known as the 'wash' still), which produces a distillate of more than 20% alcohol known as 'low wines'. This is further distilled in a second copper pot still – the 'spirit still'. From this three fractions are collected: the first fraction (known as 'foreshots' or 'heads'), contains volatile components (such as methanol, acetaldehyde, diacetyl and sulphurous compounds) with undesirable flavour characteristics; and the last fraction, known as 'feints' (or 'tails'), contains higher alcohols/fusel oils (e.g., iso-butanol, propanol, amyl alcohol), other phenolic compounds and fatty acids, and is mixed with the foreshots and added to the low wines from the next batch

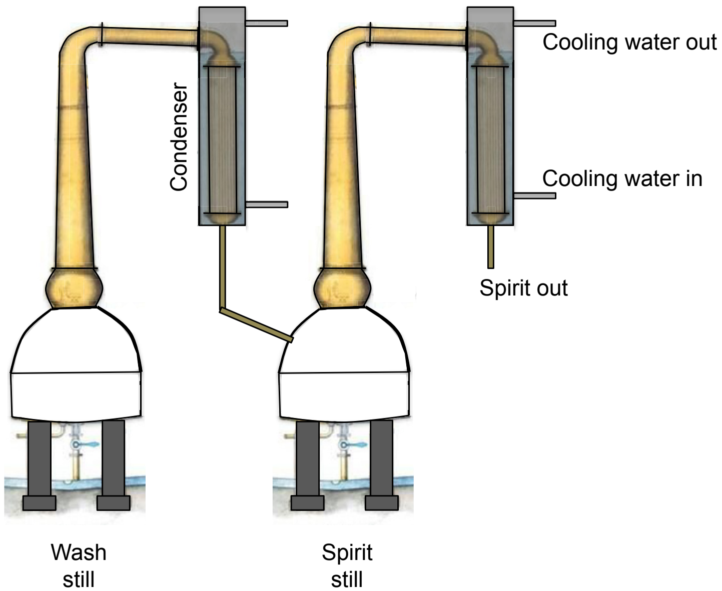


FIGURE 12.19 Sequential pot stills used in the distillation of Scotch whisky. Although one configuration is illustrated, a variety of designs, styles and layouts will be found in industry. Heads and tails will often be mixed with incoming streams for redistillation.

and redistilled. It is the middle fraction (the 'heart of the spirit') which is collected as the basis of the marketable product. It contains ~68% (65%–72%, depending upon the company) alcohol, but it has to mature in oak casks over a period of at least 3 years before sale (Bathgate, 1989).

The spent grains (known as draff and lees) may be further processed into distillers' grains or sent directly to livestock without further processing – this is discussed in more depth later in this chapter.

12.4.2 Grain whiskey

A summary of grain whiskey production is given in Fig. 12.20, and, as noted, it is somewhat different to the Scotch whisky process.

For many years the most-used raw material for distilleries in the United Kingdom was maize, which was imported from North or South America or South Africa. Due to import levies and changing economics during the 1980s, though, maize became largely displaced by wheat. Barley is a less attractive alternative, as β-glucans released during cooking produce undesirably high viscosity and spirit yields are low. The preferred wheat type is soft because of its lower protein content and the better-flavoured spirit that can be produced from it. More than half of the wheat used usually comes from Scotland, the remainder coming from elsewhere in the United

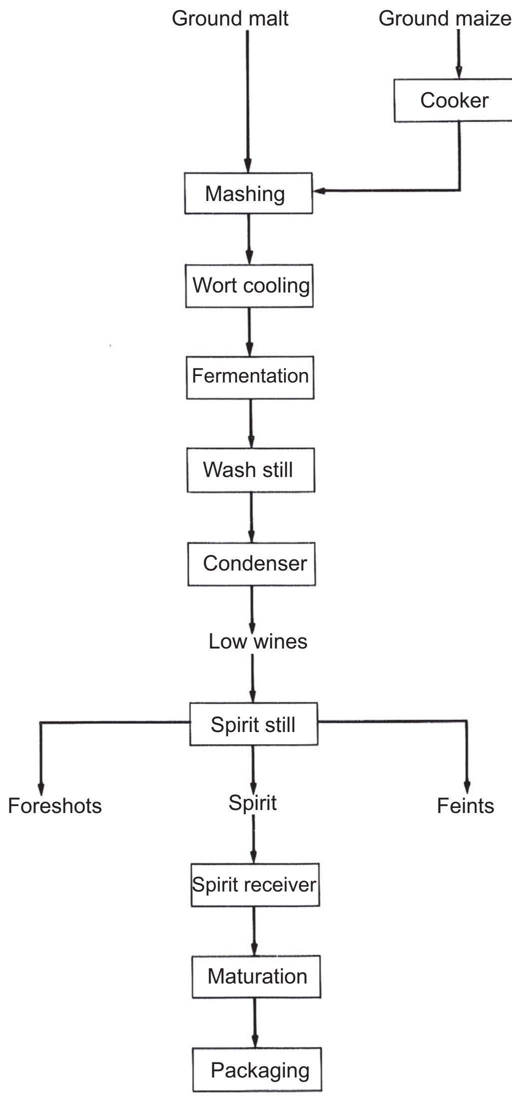


FIGURE 12.20 Flow chart summarizing the major steps in grain whiskey production.

Kingdom. In the United States and elsewhere in the world, wheat and maize are the primary substrates for whiskey production.

The mode of use of the grain varies among distilleries: in some the grain is cooked whole prior to mashing, while in others it is milled first. Mashing may be carried out in batches or as a continuous process. Individual preferences also influence the nature of the malt used, the primary variation being in the degree of kilning. The malt is milled and suspended in cold

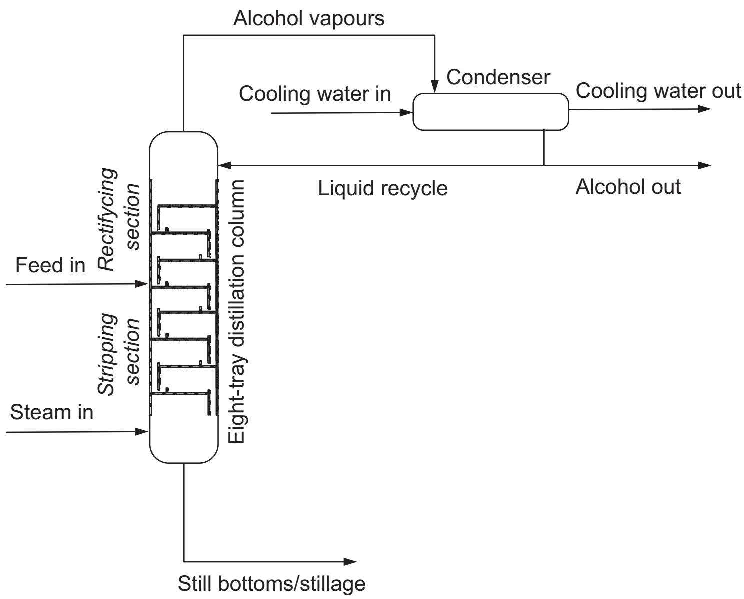


FIGURE 12.21 Eight-tray continuous distillation system showing inputs and outputs.

water before being added to the freshly cooked cereal grain. A temperature of 65°C in the combined slurries is appropriate for enzymatic conversion of the starch. Malt accounts for 8%–15% of total solids present before saccharification. Following conversion, wort is not separated and fermentation occurs in the whole cooled mash.

After fermentation, the unfermented solids, water and unwanted alcohols and other chemical compounds (as discussed previously) must be removed from the alcohol. As with malt whisky, the alcohol content is increased by multistage distillation, but in this case to a higher alcohol content of ~94%. Distillation is carried out not in pot stills but by the more economical continuous distillation method (Figs 12.21 and 12.22). Many continuous stills are based on the Coffey still, named after its purported inventor, Aeneas Coffey, who patented this process in 1830 (Bathgate, 1989). Although following the principles developed by Coffey, this method of distillation can have a variety of layouts and configurations in modern distilleries.

12.4.3 Bourbon whiskey

As defined in the United States (Code of Federal Regulations, Title 27, Part 5), bourbon whiskey must be made with at least 51% maize, be distilled to no more than 80% alcohol v/v, be aged in new, charred oak

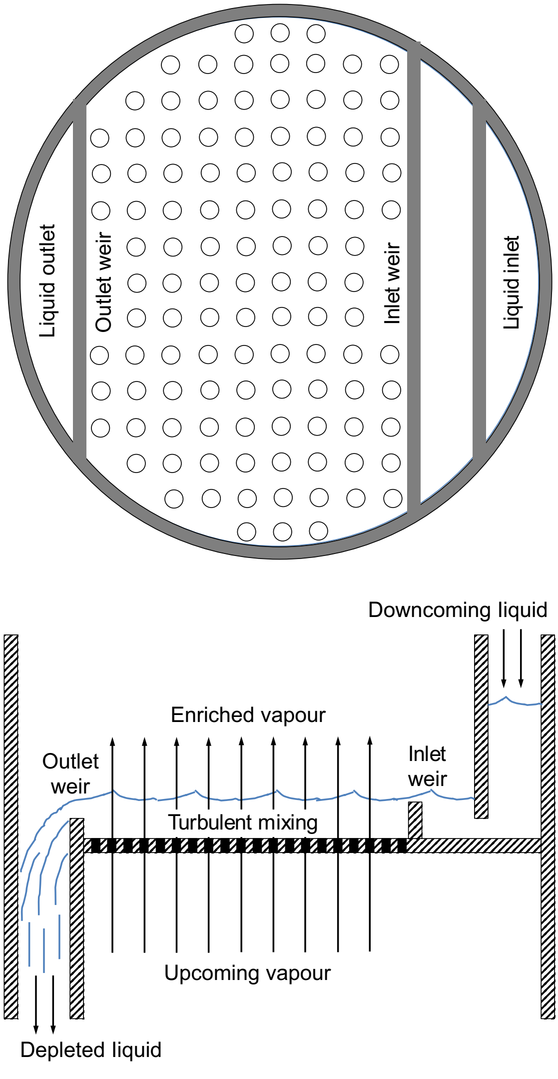


FIGURE 12.22 Circular tray for a continuous distillation column. Note that hot vapour rises through perforations, mixes with downcoming liquid and evaporates alcohol, leaving a depleted liquid to fall to the next tray. Continuous distillation columns comprise a series of stacked trays.

containers (at least 2 years to be labelled a 'straight' whiskey) and be bottled with at least 40% alcohol v/v. Blends of other cereals (often combinations of barley, wheat and rye) to be mashed with the maize are ground in a hammer mill prior to addition of malt and water. If a rye whiskey is to be made, the mash must contain at least 51% rye. Water is added at the rate of 6.0–7.4 L/kg, and some stillage (known as 'backset') may be included to adjust the pH to 5. Although a total of 10%–15% of malt is finally present, only 1%–5% is added initially, the remainder ('conversion malt') being added following cooling after the cook. Cooking consists of raising the temperature to 70°C and holding it for 30–60 min. It is cooled to 63°C for the conversion of starch to sugars to be completed. Further cooling follows before the whole mash is pumped to a fermenter, where it is pitched with 2% v/v yeast. The rise in temperature due to fermentation is not allowed to exceed 35°C. Fermentation takes about 72 h; the resulting product is known as 'drop beer', and this is then distilled in a continuous column distillation system (Fig. 12.21) (Nagodawithana, 1986).

12.4.4 Neutral spirits

The beer for neutral spirits' (e.g., vodka, grain spirits, gin, etc. – see Code of Federal Regulations, Title 27, Part 5) distillation is produced as economically as possible. Flavour is actually an undesirable attribute, so expensive means of producing flavours (as in whisky) are unnecessary. Primarily the chemistry of conversion of starch to sugars and then of sugars to alcohol must be considered. Often the cheapest source of starch is used. In countries where maize is common, that cereal is used, but elsewhere other cereals (such as wheat) may be cheaper (e.g., wheat in Russia and Canada).

For these distilled spirits, it may be more economical to use enzymes derived from microorganisms than those derived from malt. Fungal and bacterial enzymes may thus be used in this process. A further advantage is that amyloglucosidase is available from microbial sources. Adjustment of pH is achieved by use of chemicals, calcium hydroxide being added to the suspension of ground cereal introduced into the cooker to achieve pH 6.3, and dilute hydrochloric or sulphuric acid adjusting the pH to 4.5 before saccharification. Temperatures during cooking may be up to 100°C under atmospheric conditions or 160°C if high-pressure cooking is used. The pressure cooking saves time (5 min instead of 30–60 min at highest temperature).

Amylases are added at appropriate temperatures as the mash cools: bacterial at 85°C, fungal at 63°C and amyloglucosidase at 60°C. Fermentation is achieved by yeasts selected for their high rate of alcohol production and their tolerance to high alcohol levels, possibly 8%–9% or more. Continuous distillation and rectification of the resulting beer can produce an alcohol content of ~95%.

12.4.5 Craft spirits

The 20th century saw the development of large brewing and distilling companies, some on a national scale and even some on a multinational scale. A growing trend since the early 2000s, though, has been the development of small craft distilleries. Fig. 12.23 illustrates this

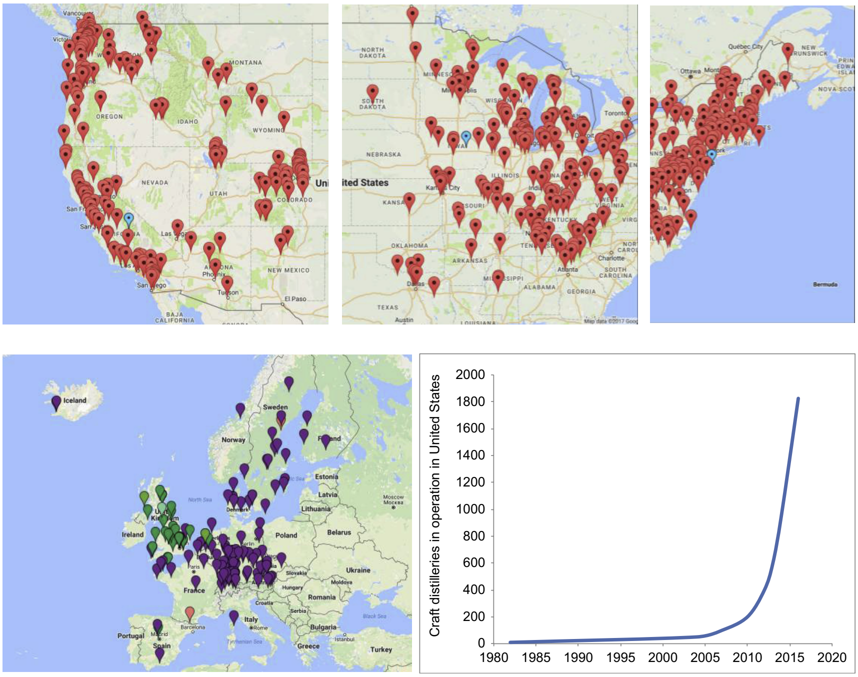


FIGURE 12.23 Google Earth maps illustrating distribution of small-scale craft distilleries that have begun operations since 1980. As of 2017, there were >2200 in the United States and >159 in Europe. *Based upon data from* www.distilling.com*, January 2017. Craft distilleries are defined as having a maximum annual sales less than 100,000 proof gallons of spirit.*

growth. This applies to all types of distilled spirits, not just whiskey. This trend has been precipitated by changes in various laws and regulations concerning the production of distilled spirits, but also a greater desire among consumers for artisan-style food and beverage products. Similar trends have been seen in the craft beer and wine industries.

Further technical details and several of the latest developments in distilled beverage production can be found in Bryce et al. (2008) and Russell (2003).

12.5 FUEL ETHANOL

During the 2000s the maize-based ethanol industry grew exponentially in the United States due to changes in government policies regarding renewable energy (Fig. 12.24) and implementation of the Renewable Fuel Standard (https://www.epa.gov/renewable-fuel-standard-program). Production and use of biofuels in other countries grew as well. Currently, the Renewable Fuel Standard in the United States mandates the use of 15 billion gal (56.8 billion L)

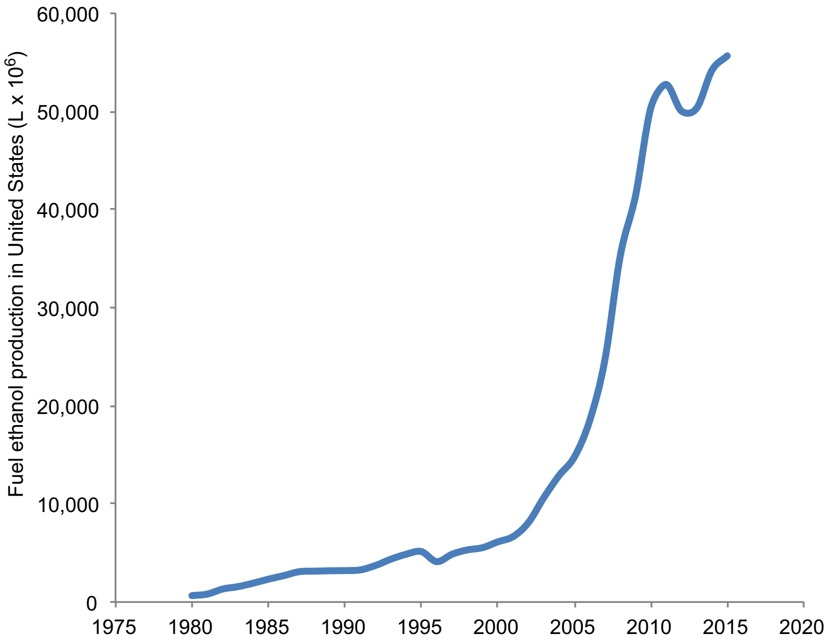


FIGURE 12.24 Production of fuel ethanol in the United States over time. *Based upon data from* www.ethanolrfa.org, *January 2017.*

annually – most of this comes from corn-based fuel ethanol. Many other countries have also developed similar mandates. Cereal grains are the most common substrate for the production of industrial alcohol.

Ethanol (ethyl alcohol) is highly combustible and has a long history of use as a motor fuel. As with beer and distilled spirits, it is produced by the metabolism of glucose by yeast (*Saccharomyces cerevisiae*); the glucose is produced by the hydrolysis of starch. In fact, since all cereal grains contain a large proportion of starch, it is technically possible to obtain ethanol from any cereal. Recall, this happens when cereal grains are malted and then brewed to make beer or distilled spirits, which are aqueous solutions of alcohol. The production of ethanol can actually be regarded as a modification of the brewing process, in which grain starch is the starting material and pure ethanol, rather than an aqueous solution, is the final product. Thus the industrial production of ethanol closely resembles the production of distilled spirits, although commercial enzymes are used, not those naturally present in the grain (i.e., the grain is not malted).

Ethanol has, in fact, a long history of use in internal combustion engines. In 1826 Samuel Morey (United States) invented a combustion engine that used ethanol and turpentine as fuel; in 1860 Nicholas Otto (Germany) invented a combustion engine that ran on pure ethanol; in 1896 Henry

Ford's (United States) quadricycle, his first automobile, was developed – it used ethanol as a fuel; and in 1908 the Hart-Parr Company (United States) manufactured farm tractors that used ethanol. The history of ethanol as a fuel is replete with many examples of setbacks and advances, drama and politics (Benton et al., 2010).

The principal reasons for making ethanol from cereals are that ethanol can be effectively used as a partial or even complete replacement for petroleum-based gasoline as a fuel for internal combustion engines; it is a domestic source of fuel; manufacturing of ethanol is a useful way of dealing with grain surpluses whenever they arise; and development of the biofuels industry can increase the number of jobs in rural localities. Historically, interest in the production of biofuels tends to increase when fuel shortages occur, when fuel prices are high and/or when prices for grains are depressed.

For example, a wheat surplus in Sweden in 1984 was dealt with by establishing a plant that separated the starch from a residue to be used for animal feed. About half the starch (the best quality) was to be used by the paper industry, and the remainder for production of ethanol.

The maximum theoretical yield of ethanol varies according to the type of cereal used: 431 L/t (2.9 gal/bu) from maize, 430 L/t from rice, 340–360 L/t from wheat and 240–250 L/t from barley and oats (Dale, 1991). Of course, due to inefficiencies in factory processing operations, achieving maximum theoretical yield is often challenging and some plants never achieve these levels. As a practical rule of thumb, 1 bu of maize (25.5 kg) will yield ~2.8 gal (10.98 L) of ethanol, and approximately 17–18 lb (7.7–8.2 kg) each of CO_2 and nonfermentable materials (e.g., proteins, lipids, fibres, minerals, etc.) – which are processed and then sold as distillers' grains.

The process of manufacture of ethanol from cereals (Fig. 12.25) closely resembles that already discussed for the production of distilled spirits, but on a much larger industrial scale. An overhead plan view for a typical ethanol facility is depicted in Fig. 12.26. One of the largest ethanol plants in the United States is shown in Fig. 12.27, while a small plant is shown in Fig. 12.28.

The production process begins by grinding the grain (Fig. 12.29) and then cooking it with water and acid or alkali (to adjust pH). Alpha-amylase and glucoamylase enzymes are added (the malting process is just too expensive and time consuming) to the cooled mash to promote the hydrolysis of starch to glucose, and the whole mash is then fermented with yeast (Fig. 12.30; fermentation vessels are nearly 1 million gal/3.8 million L), releasing carbon dioxide gas and producing alcohol. After fermentation the slurry is treated with steam in a series of continuous multitray distillation columns (Fig. 12.21), where the alcohol is separated in a rectification column, yielding 95% ethanol (5% water); the remaining water is removed from the purified ethanol by a molecular sieve technology which uses a

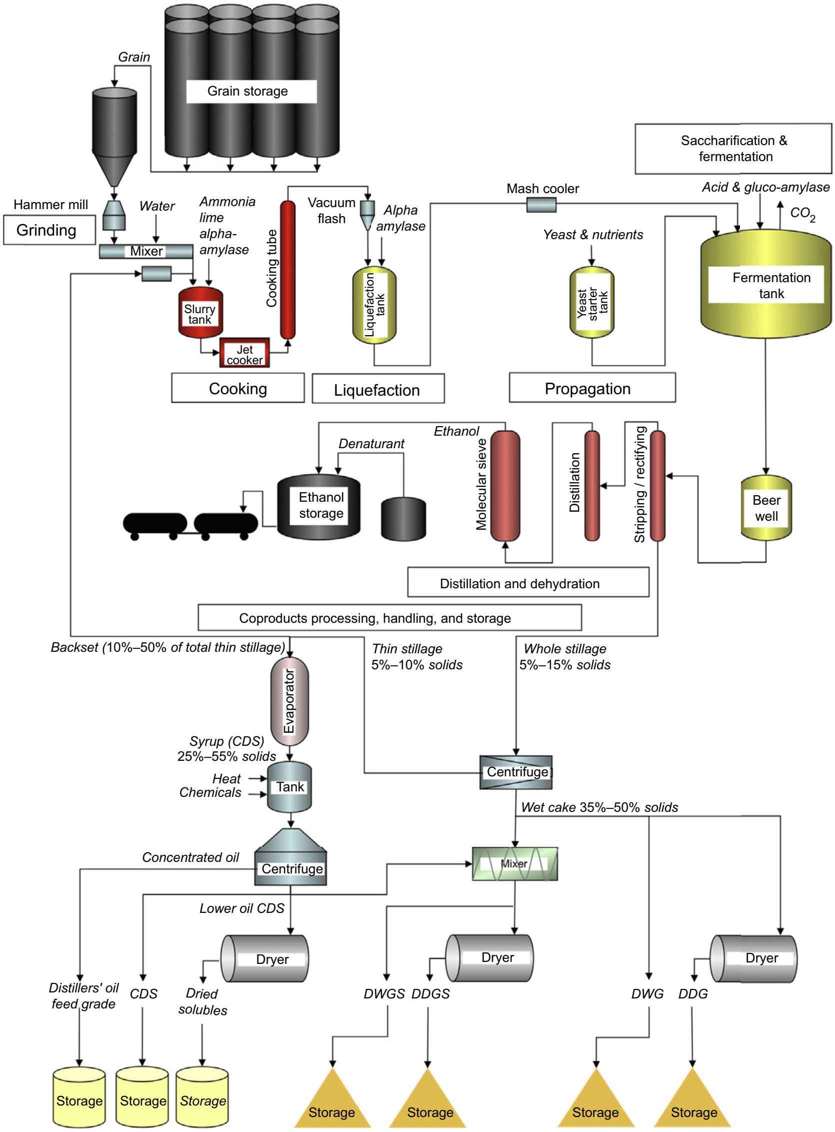


FIGURE 12.25 Flow chart summarizing the major steps in grain-based fuel ethanol processing. *Based, in part, on Rosentrater, K.A., 2011b. Manufacturing of fuel ethanol and distillers grains – current and evolving processes (Chapter 5). In: Liu, K., Rosentrater, K.A. (Eds.), Distillers Grains: Production, Processing, and Utilization. CRC Press, Boca Raton, FL, USA.*

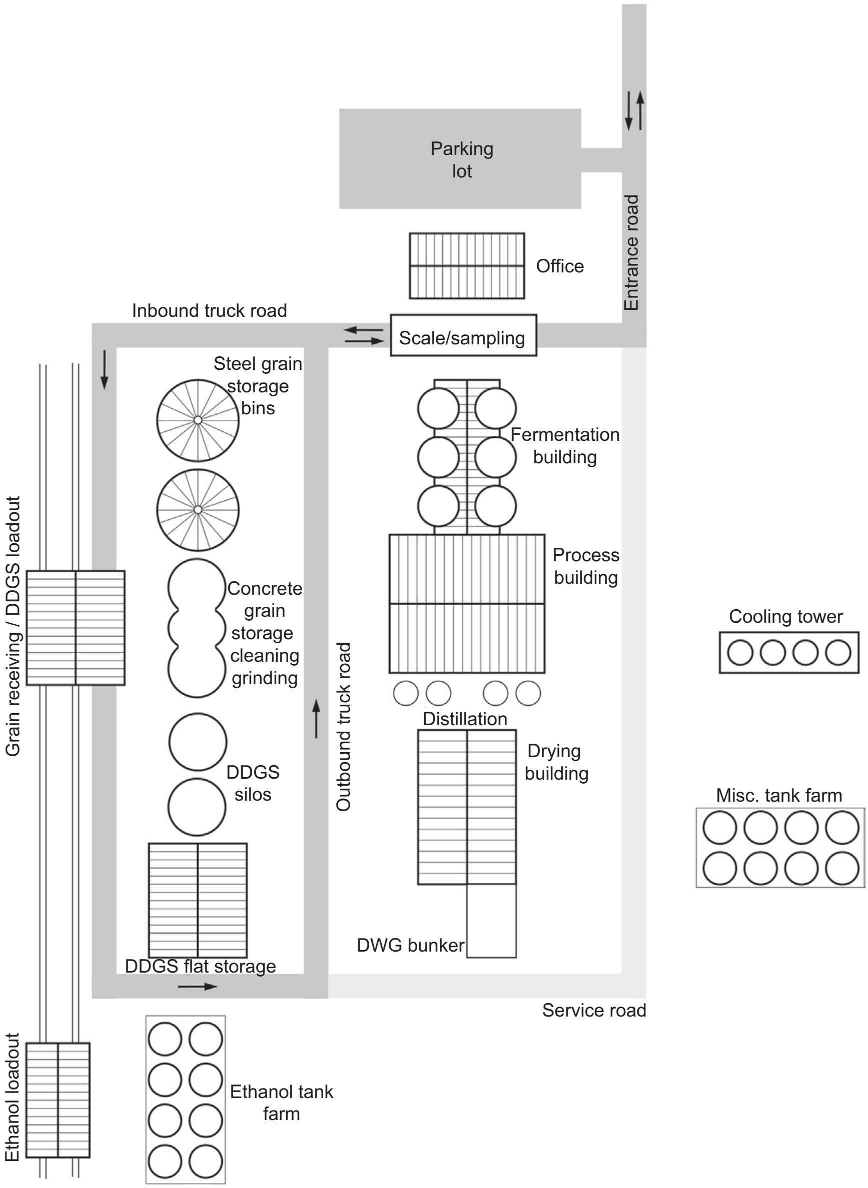


FIGURE 12.26 Overall plan view of a fuel ethanol processing facility, showing typical locations and sizes of structures. *Based, in part, on Rosentrater, K.A., 2011b. Manufacturing of fuel ethanol and distillers grains – current and evolving processes (Chapter 5). In: Liu, K., Rosentrater, K.A. (Eds.), Distillers Grains: Production, Processing, and Utilization. CRC Press, Boca Raton, FL, USA.*

FIGURE 12.27 Example of a large-scale ethanol processing facility (~450 million L/y).

FIGURE 12.28 Example of a small-scale ethanol processing facility (~79 million L/y).

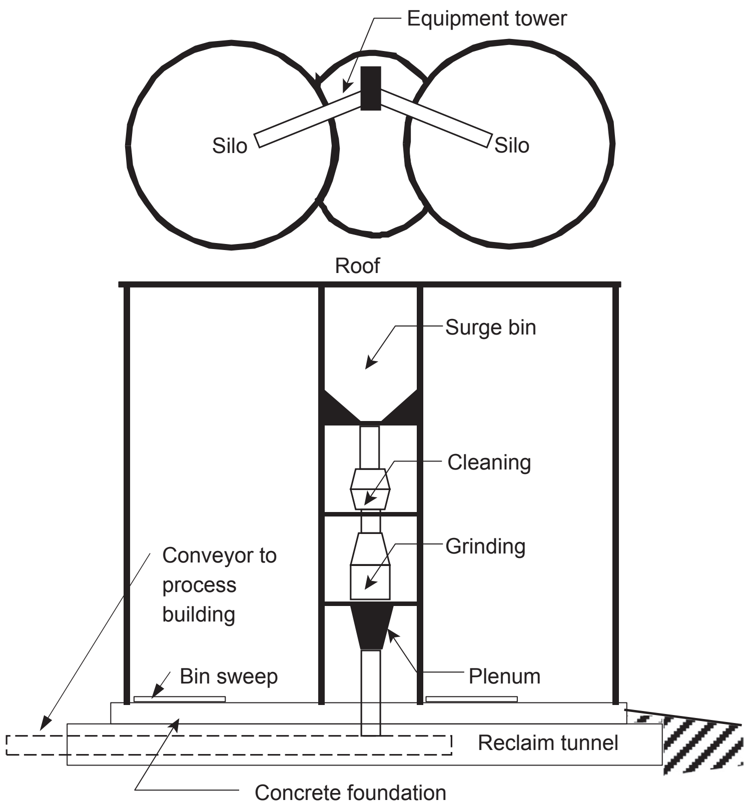


FIGURE 12.29 Typical grain storage structure for a large-scale ethanol processing facility, illustrating large-diameter concrete silos with a central surge bin, and cleaning and grinding equipment housed within. *Based, in part, on Williams, G.D. and Rosentrater, K.A., 2006. Design Considerations for the Construction and Operation of Ethanol Facilities. Part 1: Planning, Structural, and Life Safety Considerations. Paper 064115. Annual Meeting of the American Society of Agricultural and Biological Engineers, Portland, OR, USA.*

bed of zeolite to entrap the water molecules. The still bottoms are subsequently dehydrated (through centrifuges and evaporators) to produce protein-enriched distillers' grains (Figs 12.31 and 12.32), which are used for animal feed (Dale, 1991). This is discussed later.

As a motor fuel, ethanol has various advantages over gasoline: it has a very high octane number; it increases engine power; and it burns more cleanly, producing less carbon monoxide and oxides of nitrogen. On the other hand, there may be difficulties in starting the engine on ethanol alone, and accordingly a blend of ethanol with gasoline is generally used in Europe and the United States. The down side, however, is that the energy content of ethanol is lower than that of gasoline, so fuel economy may decline to a degree when using ethanol/gasoline blends.

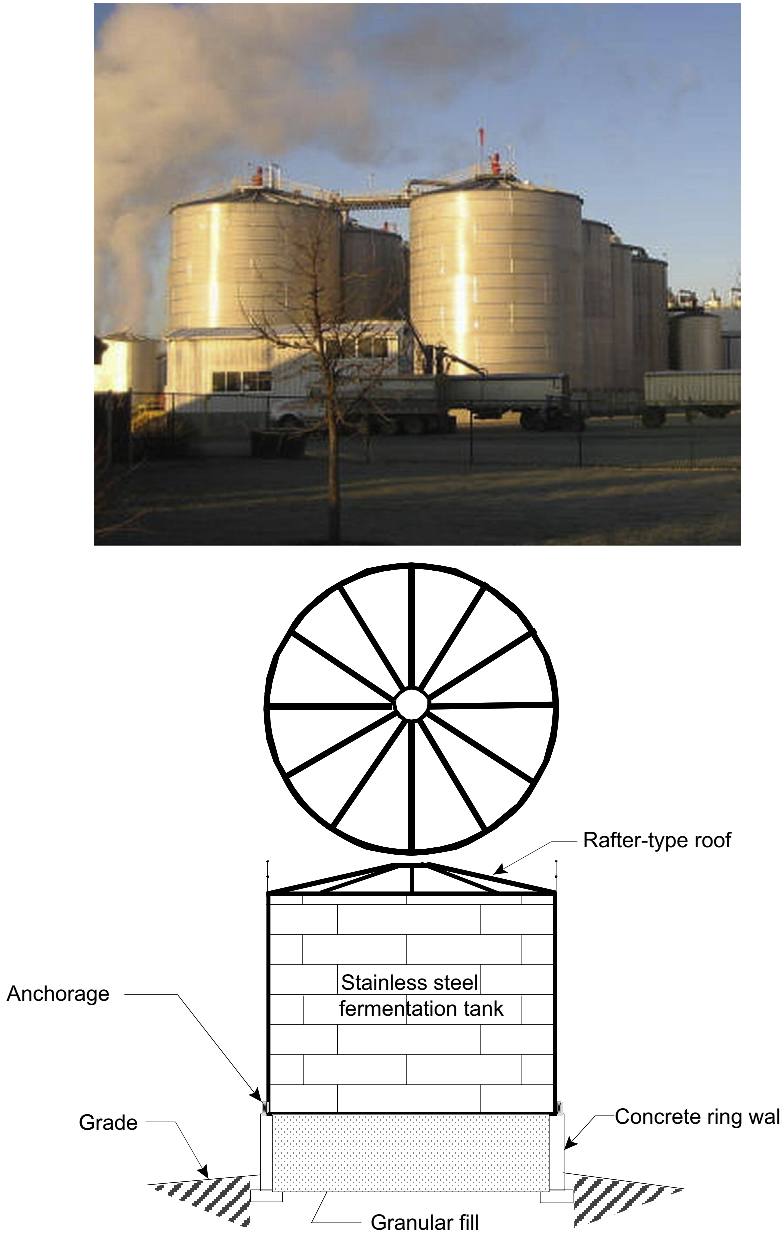


FIGURE 12.30 Typical fuel ethanol fermentation vessels, which sit upon ring foundations and are typically not enclosed in a building shell (as in beverage alcohol production). *Based, in part, on Williams, G.D., Rosentrater, K.A., 2006. Design Considerations for the Construction and Operation of Ethanol Facilities. Part 1: Planning, Structural, and Life Safety Considerations. Paper 064115. Annual Meeting of the American Society of Agricultural and Biological Engineers, Portland, OR, USA.*

FIGURE 12.31 Distillers' dried grains with solubles (DDGS) is the primary coproduct produced by fuel ethanol manufacturing plants, and consists of all nonfermented nutrients in the cereal grain (typically concentrated by a factor of 3× due to yeast metabolism). *Based, in part, on Rosentrater, K.A. 2011a. Overview of fuel ethanol production and distillers grains (Chapter 2). In: Liu, K., Rosentrater, K.A. (Eds.), Distillers Grains: Production, Processing, and Utilization. CRC Press, Boca Raton, FL, USA.*

Other industrial uses for ethanol made from cereal grains, besides motor fuel, include solvents, in antifreeze, and as a raw material for the manufacture of various industrial chemicals, e.g., acetaldehyde, ethyl acetate, acetic acid, glycols, etc. (Dale, 1991).

The carbon dioxide evolved during the fermentation stage finds uses in oilfields, for recovery of additional oil; in the manufacture of methanol; as a refrigerant; and most commonly in carbonated beverages (Dale, 1991). Capture and use of CO_2 are highly dependent upon plant location, the potential market demand and the economics involved in capturing, compressing and transporting this product to market.

The biofuels industry is dynamic, and the evolution and refinement of new processes are constantly ongoing. Some of these are described by technology providers (a few of which are http://www.katzen.com; www.icminc.com; www.poet.com). Extensive discussions about many aspects of biofuels' production using cereal grains and other cellulosic substrates can be found in Ingledew et al. (2009). Evolutions include techniques for increased energy efficiency, water efficiency, fermentation completeness

FIGURE 12.32 Distillers' dried grains with solubles (DDGS) storage typically occurs in either steel-sided flat storage buildings or concrete silos. *Based, in part, on Rosentrater, K.A., 2011b. Manufacturing of fuel ethanol and distillers grains – current and evolving processes (Chapter 5). In: Liu, K., Rosentrater, K.A. (Eds.), Distillers Grains: Production, Processing, and Utilization. CRC Press, Boca Raton, FL, USA.*

and efficiency, new strains of yeast and enzymes, and fractionation or concentration of various chemical constituents from the coproduct streams (e.g., proteins, fibres, oils, etc.) (Rosentrater, 2015).

A few examples follow. A process for the continuous production of ethanol from cereals, involving screening, filtering, saccharification, fermentation and distillation stages, has been patented (Technipetrol SPA, 1989), while a dual-purpose flour mill has been described in which the flour is air-classified to produce a high protein fraction (particle size 2–5 μm) and a residual protein-depleted fraction for use as the starting material for production of ethanol (Bonnet and Willm, 1989).

Extrusion cooking has been suggested as a method for pretreating grain to be used for the production of ethanol. The thermomechanical effects of extrusion cooking produce gelatinization and liquefaction of the starch so no liquefying enzyme is needed for the subsequent saccharification with glucoamylase. Ethanol yields from wet-extruded and steam-cooked grain were almost equal, but the extrusion method used less energy. Roller-milled whole barley, wheat or oats can be used in this process, with or without the addition of thermostable *alpha*-amylase, which appears to have little effect during extrusion cooking. The fermentation stage is carried out using either yeast (*Saccharomyces cerevisiae*) or the bacterium *Zymomonas mobilis*, the latter producing an increased initial rate of fermentation (Linko, 1989a,b). To date, however, this approach has been too expensive to implement commercially.

It is not just the starch in the grains that can be converted into ethanol: the cellulose and hemicellulose in any biological material can be transformed into biofuel. For example, corncobs can be used for the production of ethanol, and also of furfural (*vide infra*). By treating the cobs with dilute sulphuric acid, 80% of the pentosans in the cobs are converted to pentoses, from which furfural is obtained, while the residual cellulose can be hydrolysed to glucose with 65% yield (Clark and Lathrop, 1953).

The most promising raw materials for lingo-cellulosic biofuels, at least for widespread economic commercial adoption, include corn stover (e.g., leaves, cobs, stalks), residual straw from various cereal grains and forestry/wood wastes. During the tremendous growth in biofuel development in the early 2000s an enormous amount of research was conducted into developing materials and methods for production of biofuels from a variety of substrates. There have even been a few commercial factories opened. Covering these concepts is beyond the scope of this text, but the reader is referred to other sources for more information (dos Santos Bernardes, 2011; Biernat, 2015; Jacob-Lopes and Queiroz Zepka, 2017).

12.6 BY-PRODUCTS OF BREWING AND DISTILLING

This chapter focuses on techniques for commercially producing alcohol in a variety of final forms. But each conversion process discussed will also yield by-products (i.e., nonfermentable materials): malt sprouts, brewers' grains, *kasu* cake, spent lees, draff and distillers' grains. Of these, the largest quantities of by-products consist of the solids remaining after the final separation, leaving spent grains; in brewing, distilled spirits and biofuels these are termed brewers' grains, distillers' dark grains (known as DDG) and distillers' dried grains (also known as DDG), respectively. Historically these have been valuable for cattle feed, but animal scientists and nutritionists have conducted myriad studies

TABLE 12.6 Typical chemical compositions of various alcohol coproducts used as feed ingredients for animals (the majority [~99%] of use consists of beef, dairy, swine, poultry)

	Malt sprouts (barley culms), dried	Brewers' grains, fresh	Brewers' grains, dried	Draff (barley distillers' grains), fresh	Malt distillers' dark grains, dried	Pot ale syrup, fresh
Dry matter (%)	89.9	24.9	91.0	24.1	90.7	48.3
Protein (% db)	23.5	25.9	25.8	20.3	27.8	37.4
Lysine (% of protein)	4.6		3.1		4.3	
Methionine (% of protein)	1.4		1.5		1.4	
Lipid (% db)	1.7	7.0	6.7	8.2	8.5	0.2
Fibre (% db)	13.5	16.4	15.8	17.6	11.6	0.2
NDF (% db)*	45.2	49.6	56.3	65.1	39.7	0.6
Starch (% db)	14.7	5.7	7.8	1.8	3.2	1.8
Ash (% db)	6.0	4.1	4.6	3.3	5.8	9.5
Phosphorus (g/kg db)	6.1	5.8	5.7	3.3	9.7	19.0
Potassium (g/kg db)	17.5	1.6	2.9	0.3	10.5	22.3
Zinc (mg/kg db)	108.0	83.0	89.0	188.0	57.0	22.0
Copper (mg/kg db)	14.0	14.0	19.0	15.0	49.0	95.0
Iron (mg/kg db)	558.0	138.0	130.0		231.0	

	Corn, thin stillage, fresh	Corn distillers' wet grains with solubles (DWGS)	Corn distillers' dried grains with solubles (DDGS)	Rye distillers' dried grains with solubles (DDGS)	Sorghum distillers' dried grains with solubles (DDGS)	Wheat distillers' dried grains with solubles (DDGS)
Dry matter (%)	4.7	35.2	89.0	92.2	89.9	90.6
Protein (% db)	17.9	31.8	29.5	31.3	33.5	37.3
Lysine (% of protein)		3.0	3.0		2.9	2.3

TABLE 12.6 Typical chemical compositions of various alcohol coproducts used as feed ingredients for animals (the majority [~99%] of use consists of beef, dairy, swine, poultry) — cont'd

	Corn, thin stillage, fresh	Corn distillers' wet grains with solubles (DWGS)	Corn distillers' dried grains with solubles (DDGS)	Rye distillers' dried grains with solubles (DDGS)	Sorghum distillers' dried grains with solubles (DDGS)	Wheat distillers' dried grains with solubles (DDGS)
Methionine (% of protein)		1.8	2.0		1.8	1.5
Lipid (% db)	9.2	13.0	11.1	7.9	9.4	5.0
Fibre (% db)		8.2	7.9	8.2	8.1	7.7
NDF (% db)*	12.5	39.0	34.2		38.5	34.0
Starch (% db)	25.1	4.9	9.3			4.2
Ash (% db)	6.3	3.8	5.4	5.4	4.5	5.9
Phosphorus (g/kg db)		8.2	7.9	8.0	7.4	9.1
Potassium (g/kg db)		9.5	10.3	16.0	3.5	10.9
Zinc (mg/kg db)		63.0	62.0	70.0		130.0
Copper (mg/kg db)		6.0	6.0	27.0		10.0
Iron (mg/kg db)		116.0	123.0	154.0		

* *NDF, neutral detergent fibre.*

Based upon data from Feedipedia – Animal Feed Resources Information System, 2017. INRA CIRAD AFZ and FAO. www.feedipedia.org.

over the years, and these products are now readily used not only in ruminant (e.g., beef, dairy) diets but also in monogastric (swine, poultry, fish and other) feeds.

Although not so essential to the profitability of beverage alcohol plants, sales of these materials are critical to the profitability of ethanol plants and they truly have become coproducts (in addition to biofuel, the primary product). Table 12.6 provides typical compositions for many of these feed products. Comprehensive reviews of physical and nutritional properties, use in various species and processing evolutions are provided in Crawshaw (2001) and Liu and Rosentrater (2011), to which the reader is referred for more information.

Yeast is recoverable and saleable, and CO_2 may be worth harvesting for sale if produced in sufficient quantity and in an appropriate locality. Fusel oils, including the components furfural, ethyl acetate, ethyl lactate, ethyl decanoate, *n*-propanol, iso-butanol and amyl alcohol, are used in the perfume and other industries (Walker, 1988).

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