BEER AND BREWING

1. Introduction

Beer (Latin: bibere, to drink. Old English, beor. Middle English, bere) may be defined as a mildly alcoholic beverage made by the fermentation of an aqueous extract of cereals (grains). Cereals contain carbohydrates, mainly in the form of starch, which brewers' yeasts cannot ferment, and so breakdown of starch to fermentable sugar is a central feature of beer-making processes. This is in contrast to wines in which fermentable sugars are preformed in the raw materials (eg, fruits such as grapes). Thus, sake, for eg, commonly called a rice wine, is in fact a beer. The grain mainly used for beer-making is barley, with rice and corn as adjunct, and some beers are made partly from malted wheat. Others grains such as sorghum can be used, especially in the manufacture of traditional beers, and oats in, eg, a few stouts.

Manufacture of beer has five main stages: (*1*) malting, (*2*) brewing, (*3*) fermentation, (*4*) finishing, and (*5*) packaging. This article begins with an overview of the whole process, then reviews malting and malt and other raw materials. It then follows the brewing process and fermentation from beginning to end. It concludes with some brief comments on the history of beer and its healthful value. North American brewing practices are taken as standard in this article.

2. Brief History

Beer has a long history doubtless dating to the first settled communities based on agriculture and growing grain. This was probably in the Tigris and Euphrates valleys some 10,000 or more years ago. Barley was one of the first grains cultivated and was processed in a number of ways, especially, eg, bread-making, to make it edible. From these processes, brewing likely developed; eg, if the ancients (by accident or design) used partially germinated grain to make bread they would have completed the basic processes of malting and mashing. Grain-based beverages arose independently in many cultures, eg, the rice-based drinks of Asia have a history dating to at least 2000 BC. Naturally, the ancients, being unaware of enzymes and microorganisms, ascribed the conversion of water and grain to intoxicating beverages to the intervention of Gods, eg, in Egypt to Osiris and his wife Isis, and to Ceres, a pre-Roman Goddess of agriculture (hence the Spanish word for beer, cerveza). By the first century AD, beer was widely known and the common drink of the Germans, the Britons, and the Irish. Tacitus, the first/second century Roman historian mentions beverages distilled from fermented grains in the British Isles. In these northern European climes barley could be grown where grapes could not and beer remains to this day a preeminent drink in these regions. Beer making has long been associated with the church especially monasteries, and in a few places (eg, the Trappist abbeys of Belgium) remains so. From these origins, and widespread domestic brewing, arose the first commercial enterprises around the twelfth century and, with that, brewers' organizations, regulation, taxation, and licensing as we know it today. Beer came to North America with the first European settlers; indeed the landing at Plymouth Rock was because "—our victuals were much spent especially our beere—". Throughout the early years of history of the United States, beer was actively promoted as the beverage of temperance in preference to spiritous liquors, and our first presidents were ardent home brewers. Beer became embroiled in the turmoil over Prohibition because by the mid-1800s the brewing industry in the USA was almost entirely controlled by Germans, and German was the language of the brewing profession. Anti-German feelings brought on by World War I caused beer to be included in Prohibition. The Volstead Act (Prohibition) passed in 1919 and was repealed in 1933. Brewing was, and is, very much involved with the scientific advances of the day, eg, brewers immediately adopted the discoveries of Louis Pasteur. Brewers enthusiastically embraced new technologies such as the steam engine and refrigeration as they became available. They assiduously followed and contributed to advances in biology, especially enzymology and microbiology, which particularly met the brewers' need to understand their processes in scientific ways. This continues today and brewing laboratories have most modern instruments of analysis, eg, and support and maintain active research programs. Brewers also maintain an interest in contemporary genetics, though the politics of genetically modified organisms (GMOs) is too complex to permit application of these techniques to brewing processes and products.

3. Overview of the Process

Beer is a food product and subject to all the regulations concerning food production and distribution. Malthouses and breweries therefore are impeccably clean and sanitary places not only to meet the provisions of those regulations but also because the brewing process and beer itself are subject to attack by unwanted microorganisms. While these organisms pose no danger from the point of view of transmitting illness to the consumer, they can easily spoil beer flavor, eg, by causing sour tastes and unwanted aromas and by forming hazes.

Malting takes ~8 days. However, the malt spends a good deal more time than that in the malthouse before it is sold to brewers because it needs to be cleaned, matured, analyzed, and then blended to meet brewers' specification before sale. In the malting process, barley is first wetted (steeped) for 2 days and then put to germinate in an appropriate vessel where it is aerated and turned regularly for ~4 or 5 days. Then, heating in a kiln for up to 2 days dries the green malt. This imbues the product with intense malty flavors and color, both of which become part of the character of the beer made from it. *Brewing* (Fig. 1) follows malting. In the brewhouse, five distinct stages occur in a period of ~5–6 h: (*1*) the malt is milled (ground up) and then mixed with suitable water and (*2*) heated through a precise temperature program (mashed). This converts starch to fermentable sugar. The liquid mass is then transferred (*3*) to a device to separate the insoluble spent grains (mainly the husk of the malt and precipitated protein) from the sugary aqueous extract called wort. The wort is then boiled (*4*) with hops, to stabilize it and to impart bitterness. The spent hops are removed (*5*) and the wort is then cooled, which concludes the brewhouse operations. Note that there may be several brews at different stages in the brewhouse at one time, and so one brew might emerge from the brewhouse every 2–3 h or so from each line of brewing vessels. *Fermentation* follows (Fig. 1 continued): A desirable yeast culture is added to the wort and during the course of ~3–9 days (depending on temperature) the yeast converts the sugar present mainly into alcohol and carbon dioxide, but also forms a myriad of flavor compounds that, with the flavors from malt and hops, combine to create the final beer flavor. After this primary fermentation the beer is *finished*, ie matured (aged) and carbonated by further treatments, eg, secondary fermentation. It is then filtered to make it brilliantly clear and stabilized to prevent changes in the market place.

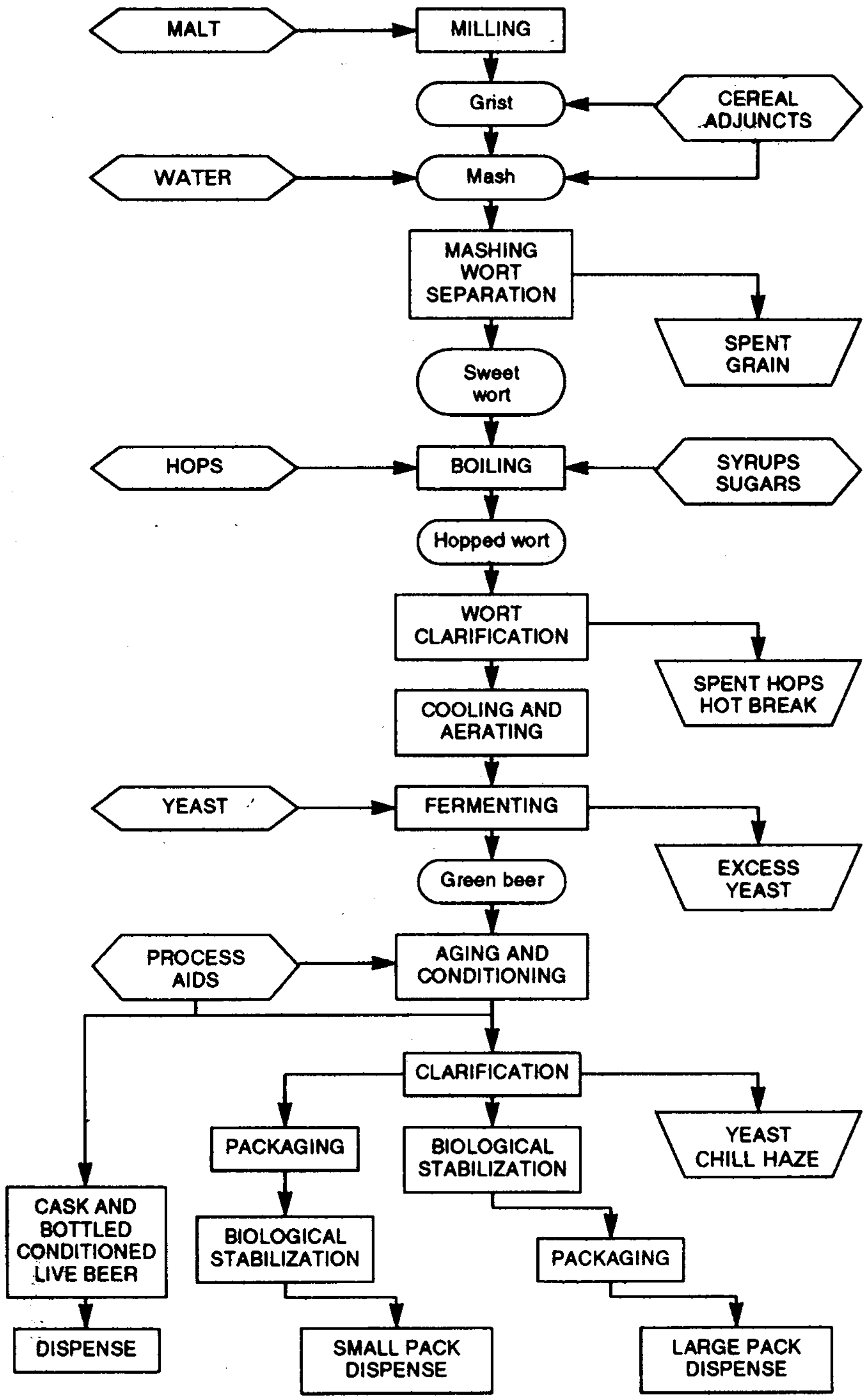

Fig. 1. An outline of brewing and fermentation from raw materials to dispense. (From Ref. 1, with permission).

Finally this beer is *packaged* at high speed into bottles and cans of various convenient sizes and into kegs for sale with strict control of oxygen access.

4. Malting

The objective of malting is to achieve "modification" of the barley grain. Barley lacks suitable enzymes for brewing, lacks friability (ie, it is a hard grain) and so is difficult to mill, it lacks suitable aroma and flavor and color, it lacks simple nitrogenous compounds suitable for yeast growth, and it contains β-glucans, which make aqueous barley extracts viscous and difficult to filter. Modification, which is the sum of changes as barley is converted into malt, and is achieved by partially germinating the grain, solves all of these problems when done well. Barley, unlike wheat, has an adherent husk that protects the grain during malting.

Malt is made from barleys that are approved or selected varieties known as malting barleys and that meet necessary specifications. These barleys generally do not yield as large a crop as feed barleys and so maltsters pay a premium to farmers to plant malting varieties and to meet malting grade. Typically, malting barleys tend to germinate vigorously, modify evenly and completely, have a low nitrogen or protein content, and are relatively plump, ie, tend to have large kernels that contain a lot of starch relative to the amount of husk. In North America, barley for malting is grown in the most northerly United States and Canada and at equivalent latitudes elsewhere; it is harvested only once a year and so it is necessary to store it in silos for up to a year or more before it is used. There are two kinds of malting barleys, six- and two-row, and brewers use blends of both kinds. Generally, malts made from six-row barleys tend to yield rather more enzymes (expressed as diastatic power, DP, or starch-splitting ability) than malts from two-row barleys. On the other hand, malts made from two-row barleys yield a little more extract (more soluble solids to the wort) than six-row barleys.

Barley arrives at the storage silos as a raw agricultural product and the process of converting it to food for humans begins immediately. It is cleaned to remove dust and stones (especially important from the point of view of preventing sparks and potential dust explosions) twigs and straw and separated from foreign seeds and skinned and broken corns. These materials reduce the storage stability of the grain by encouraging insects and molds in the silos. Barley contains living tissue and respiration (breathing) takes place. The grain must therefore be moved from time to time to aerate it and it is recleaned and fumigated if necessary. For stable storage, barley moisture should be ~12–13% and conditions of storage must be dry and cool. The barley variety must be capable of remaining viable (alive) throughout storage. Barley often enters storage in a dormant state depending on the variety and growing conditions and dryness; ie, it is alive but not yet capable of growing (germinating). During storage the grain comes out of dormancy and is then ready for malting.

The cleaned and separated barley is graded before malting, because plump and thin corns germinate at different rates that would affect the evenness of the resulting malt. The plumpest corns are made into malt for use in brewing, but thinner corns can be malted in special ways for use in distilleries or for flavoring malts or baking or confectionery use. There are three stages of malting: steeping, germination, and kilning. In *steeping*, the barley is soaked typically in a conical-bottomed steep tank in potable water at ~10–15°C for up to 48 h. The batch size might be 40,000 lb. The moisture content of the grain rises from ~12% to a level decided in advance by the maltster, which will be in the range of 42–46% moisture. This choice affects the speed and course of germination and so malt characteristics. During steeping the water is changed several times and the steep is vigorously aerated to provide oxygen for the kernels, which are beginning to respire. This also agitates and effectively cleans the grain and 1–2% or more of grain weight is lost by this washing. Toward the end of steeping the "chit" (the tip of the emerging rootlet) appears and at this stage the grain is transferred to the germination vessel where the maltster is better able to meet the needs of the growing grain and to control the process.

One of several designs of *germination* vessels might be used, eg, large horizontal drums that rotate, or large flat boxes that have turners traveling up and down (Fig. 2), or circular vessels with turners rotating about the central axis. There are other choices. In all cases, however, the germination vessel achieves three objectives: (*1*) to turn the growing grain to assure the rootlets do not entangle to form an impenetrable mass; (*2*) to pass air evenly through the mass of grain so that the grain can respire; and (*3*) to maintain control of moisture and temperature (say 18–20°C) through a supply of moisture-saturated cool air. In this way the grain grows at a controlled and steady rate for ~4 or 5 days. During this time there is significant growth of the rootlets, which is obvious but gives little information about the course of the process. The shoot (also called the plumule or acrospire) grows under the husk during germination. Maltsters aim to have the acrospire of all individual kernels grow to $\frac{3}{4}$–1× the length of the kernel

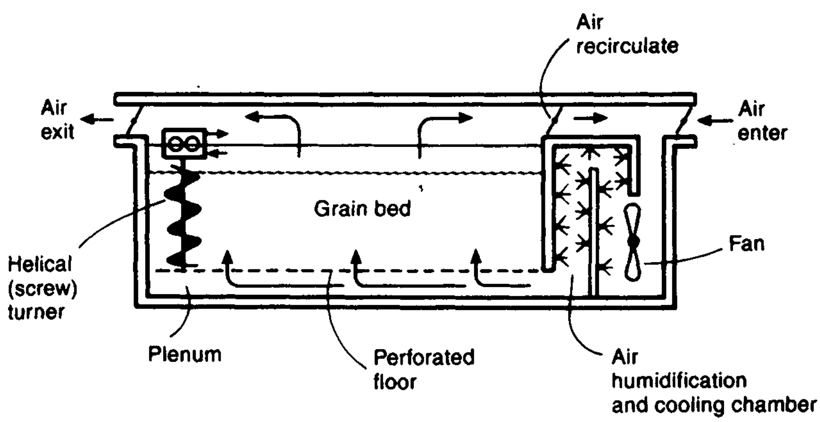

Fig. 2. A barley germination chamber must provide ample air, turning, and temperature–moisture control. Many designs are possible. The chamber might be rectangular or circular in design, or a large revolving drum can be used for germination. This is a schematic of a box or compartment germination chamber showing the typical flow of air through the grain bed. Alternatively, air may be drawn down through the bed. (From Ref. 1, with permission).

because this indicates that sufficient growth and even malt modification has been attained.

The maltster must now arrest further development of the grain and fix the properties imbued in the malt by germination. *Kilning* removes the moisture from the green malt by a flow of warm air (rising over the 2 days from say 50 to 70°C) and halts germination. In some malt houses the germination vessel can also act as a kiln, which is achieved by switching from a flow of wet/cool air to a stream of warm/dry air. These vessels are called GKVs or germination-kilning vessels. For the most part, however, maltsters operate separate facilities for kilning. Initially, kilning provides a relatively high flow of quite cool air to achieve substantial moisture removal. Later, however, more intense heat must be applied to remove moisture deeper within the grain and some associated with large molecules. Thus, there are two stages of kilning, and most kilns therefore have two floors. The hottest air flows through the lower floor, where the partially dried malt resides. Air leaving the lower floor is diluted with fresh air to increase its volume and cool it, and this air then passes through the upper kiln to carry out the initial drying of green malt. Thus, each batch of malt passes through the kiln in two stages, first on the upper floor and then on the lower floor before exiting the kiln. The last stage of kilning is called "curing" and is short period (2 h or so) at high temperature (85–100°C). This serves to reduce the malt moisture to its final value of ~4% and the extra heat increases the flavor and color of the malt by toasting. At the end of kilning the shriveled rootlet can be easily removed. Ordinary pale malt does not look very different from barley, though its texture and flavor are much different. During malting there are significant losses of barley dry weight, including some starch respired to CO_2. This is called malting loss and might be 6–12% of barley dry weight depending on the kind of malt being made and the effectiveness of process control. Moisture also decreases from ~12 to ~4%. Thus from 100 kg of barley only some 80–85 kg or so of malt can be produced.

During the malting process (grain germination) three main changes that are important for brewers take place inside each grain and collectively comprise modification: (*1*) the breakdown of the cell walls (especially the β-glucans they contain) in the barley endosperm (*2*) the accumulation of enzymes not previously available in barley, especially α-amylase, and (*3*) production of low molecular weight nitrogenous compounds, especially amino acids, that help form flavor compounds and will be available for nourishment of yeast during fermentation in the brewery. Note, however, that starch is only partially hydrolyzed under the cool (say 18–20°C) conditions of germination and the bulk of barley starch remains as malt starch.

During steeping water enters each barley kernel through a region of the husk near the embryo called the micropyle and so the embryo is hydrated first (Fig. 3). The embryo also contains a hormone chemical called *gibberellic acid*, which is carried in the water entering the grain into the endosperm and especially to a thin layer of living cells that entirely surround the endosperm, called the *aleurone layer*. This layer reacts to the hormone by synthesizing new enzymes that include amylases (especially α-amylase), β-glucanases, and proteases, which, respectively, are capable of breaking down starch, β-glucans, and proteins. These are the enzymes of modification. They are released into

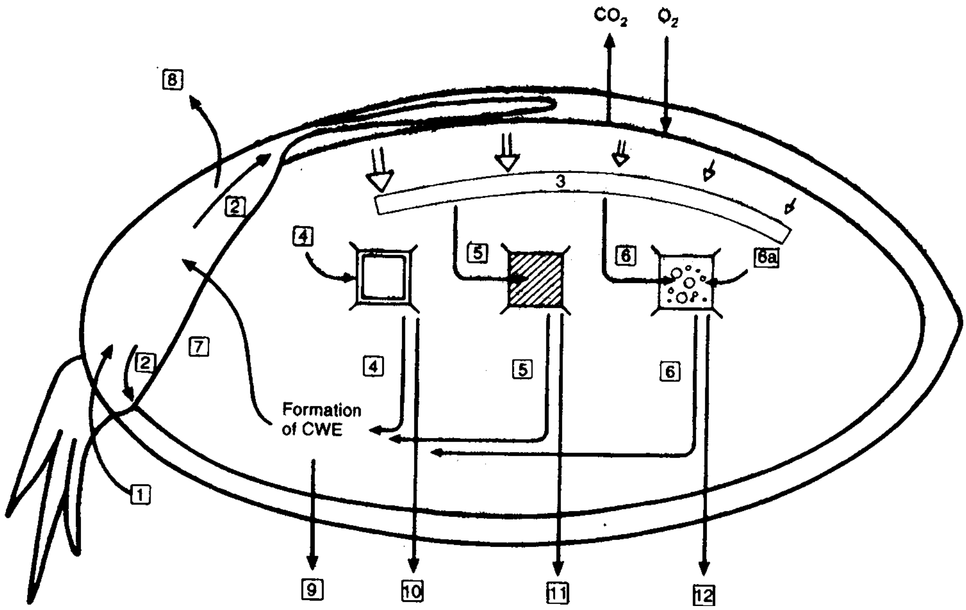

Fig. 3. Summary of events during grain germination (malting). (1) Entrance of water through the micropyle, (2) release of gibberellic acid, and (3) its progressive stimulation of the aleurone, (4) β-glucanases from the aleurone layer attack endosperm cell walls (β-glucans) to increase modification, grain friability, and to lower wort viscosity (10). (5) Proteolytic enzymes attack proteins to form amino acids (FAN) and modification expressed as S/T (soluble nitrogen/total nitrogen %) (11). (6) and (6a) Amylases initiate attack on starch, especially small starch granules, and these enzymes survive into malt (12). Also shown, (7) and (8) nutrition of the embryo causing the rootlet and shoot to grow using materials from actions 4, 5, and 6 with respiration of starch to CO_2 and water both causing malting loss; also (9) formation of low molecular weight compounds from actions 4, 5, and 6, especially amino acids and sugars that also survive into malt and extract into wort. (From Ref. 1, with permission).

the endosperm as they are formed and modify the endosperm material (amylases break down starch only slowly under the cool conditions of malting and so most of it remains in the finished malt). Because some parts of the aleurone layer are closer to the source of the hormone than others, the progress of modification is from the embryo end of the kernel toward the opposite (distal) end; therefore the least modified area of the final malt is found farthest from the embryo. If undermodified, this might be called the "steely" tip; such material is barley-like and extracts poorly in the brewhouse and may cause troublesome hazes and filtration problems downstream.

The quality of malt is gauged by a number of laboratory measures. These include (*1*) determination of Diastatic Power (DP) that is a measure of the amylase enzymes present (especially β-amylase). The value is usually between 110 and 150° for American malts. There are two amylases, α-amylase and β-amylase, that together are able to break down starch substantially (∼65–75% depending on conditions) to fermentable sugar. (*2*) Ease of milling (using an instrument called the friabilmeter), or direct determination of the β-glucan content, or the ease of extraction (called the coarse/fine difference) is used to gauge the degree

Table 1. **A Typical Malt Analysis/Specification**[a]

Physical properties	
assortment (size) (% on screens)	
on 7/64 screen	60
on 6/64	33
on 5/64	6
through screens	1
growth of shoot (length of kernel) (%)	
0–1/4	0
1/4–1/2	0
1/2–3/4	10
3/4–1	85
overgrown	5
moisture (%)	4
1000-kernel weight (g)	35
Chemical and biochemical analysis	
extract (fine grind) dry basis (%)	81.5
extract (coarse grind) dry basis (%)	80.0
coarse/fine difference (%)	1.5
enzymes	
DP (β-amylase)(dry basis)(°Lintner)	120
DU (α-amylase) (dry basis)	55
total protein (Kjeldahl-N × 6.25)	11
Wort soluble protein (%)	5
soluble protein as % of total protein (S/T)	45
wort pH	5.9
color of wort (°Lovibond)	1.8
Wort viscosity (C)	1.4

[a] From Ref. 1.

of modification. (*3*) FAN is used to measure the presence of potential yeast nutrients (amino acids, eg). The overall quality of the malt resides in its extract yield; ie, the amount of material that can be dissolved from it in a laboratory scale mashing process; the value is usually ~80%. By these measures and others (Table 1) maltsters and brewers determine the extent to which the necessary changes in barley have been achieved when producing a particular batch of malt. In practice, at the malthouse, many batches of malt are blended together to meet the brewers' specifications. The brewer is concerned with three things: (*1*) *kernel size* expressed here as assortment (by screening) and as1000-kernel weight; (*2*) *modification* expressed as growth of shoot (length of kernel), coarse/fine difference % (difference in extract between fine and coarse grind malt), and mash soluble protein expressed as a percentage of soluble over total protein (S/T%), and possibly wort viscosity; (*3*) *enzyme content* expressed as DP (mainly β-amylase) and as α-Amylase (DU, dexrinizing units).

5. Hops

Hops are a crucial component of beer although only ~4–8 oz/barrel (120–240 g/hL) are used. Their primary role is to give bitterness to beer. Although humans do not usually like bitterness, a sufficient and balanced inclusion of bitter character in beers is necessary for a satisfactory product. How the brewer handles the bitter quality of hops in creating a beer is important in differentiating one beer from another, and meeting the needs of the target consumer population. Hops also can contribute delicate aromas to beers, that, in conjunction with those flavors arising from the yeast and malt, creates the overall impression of a beer. Hops are used in the kettle-boiling process in a brewery. The key chemical reaction of wort boiling is the conversion of relatively insoluble α-acids present in the hops to quite soluble iso-α-acids (Fig. 4) that persist into the beer.

Hops grow in temperate northern climates. Oregon, Washington, and Idaho in the United States but in comparable latitudes in Britain, Germany and

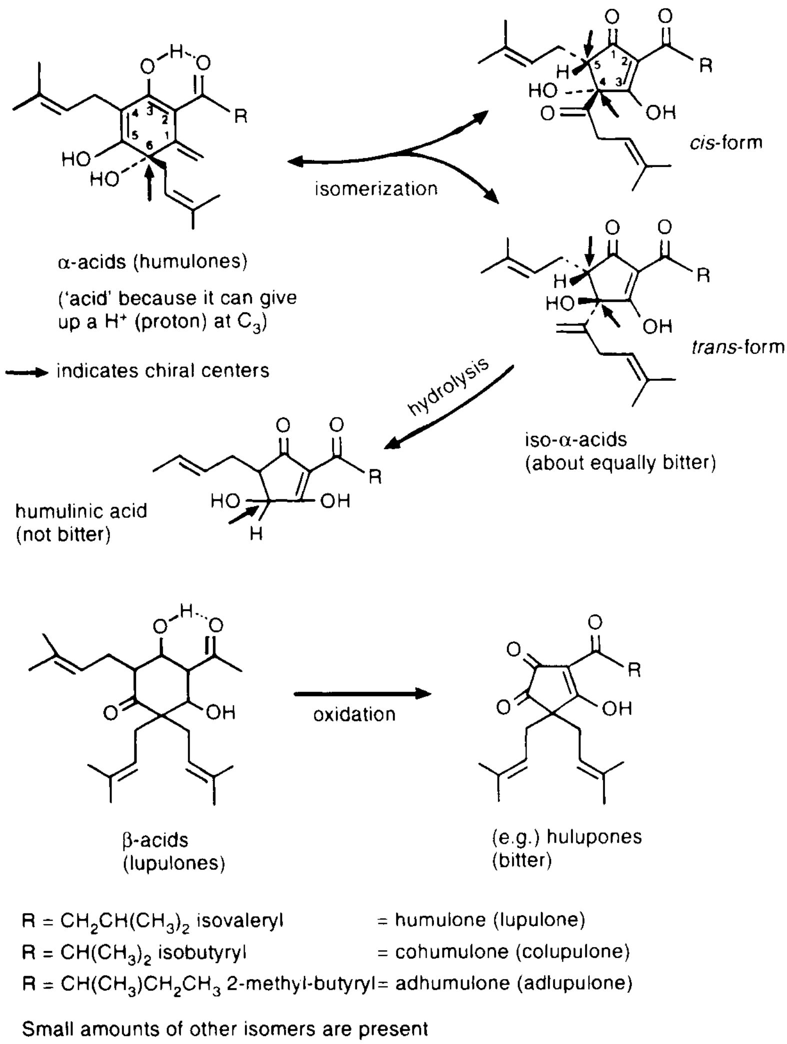

Fig. 4. Hop α-acids (above) and hop β-acids (below) and two chemical reactions of brewing significance, isomerization (above) and oxidation (below). In each case there are three major acids with different side chains, R, as identified. (From Ref. 1, with permission).

Central Europe, China and, in the Southern Hemisphere, in New Zealand and Tasmania. These latitudes are necessary for proper yield because day-length determines flowering and fruit-set and thus adequate commercial yields. Artificial light is used to grow hops at the tip of South Africa that is not quite far enough south for ideal day length. The United States and Germany are the largest producers of hops. Hops plants (*Humulus lupulus*, a member of the family *Cannabinaceae*) are perennial, dioecious (having separate male and female plants) vigorous climbing vines. Normal (ie, non-dwarf) varieties grow up strings to 15–20 ft (4–6 ms) on a strong overhead trellis called a wire-work that are permanently installed in the fields (called yards or gardens). During harvest the vine is cut back to ground level. Only the female plant is planted, although in a few places (Oregon, Britain) a few male plants are permitted because fertilization is thought to protect against some diseases. Generally, however, male plants are ruthlessly removed because brewers do not usually prefer seeded hops.

Hop "cones" are the fruit of the hop vine (though often incorrectly called the "flower"). Each cone is about the size of the top joint of a human thumb and is green and structured like a small artichoke of overlapping bracts. At the base of each bract is a bright yellow powder. These are the lupulin glands that contain the brewing value of the hops (Table 2). The lupulin glands contain the essential oils of hops that have the potential to give powerful aromas to beer and are more prized in some hops (called aroma hops) than in others, and also contain the total resins that comprise (*1*) α-acids (highly desirable as the prime source of bitterness, and the main measure of hop value and quality), (*2*) β-acids (of little value, though they can oxidize to yield bitter compounds (Fig. 4), and (*3*) the so-called hard resins (of no value). Many brewers buy hops on their content of α-acids alone, though others believe that a proper balance of bitterness and aroma is necessary for superior beers. It is necessary to process hops after harvest in such a way that their quality is conserved over perhaps a year or two.

Table 2. **Composition of Whole Dried Hops**[a]

Constituent	Percentage by weight
cellulose and lignin	40–50
soft resins[b]	
α-acids	2–17
β-acids	2–10
proteins (Kjeldahl-N × 6.25)	15
water	10–12
ash	8–10
tannins	3–6
fats and waxes	1–5
pectin	2
simple sugars	2
essential oils	0.5–3.0
amino acids	0.1

[a] The brewing value is in the resins (variable between ∼5 and 18%) especially their α-acid content because these contribute to bitterness, and the essential oils (aroma fraction).

[b] Generally those hops most prized for their aroma are lower in content of α-acids.

After harvest and separation from the vine, hops are kilned in a gentle flow of warm air (~60–80°C) to dry them to ~10% moisture. They are then heavily compacted into bales or pockets, weighing some 80–90 kg, with the intention of minimizing the entrance of air. Air can oxidize the resins (to produce hard resins) and reduce the value of hops considerably. Though cone (or whole) hops in their primary compressed state are used by a few (large) breweries, only ~30% or so of the α-acids they contain reach the beer as *iso*-α-acids; the remainder is lost along the way for various reasons, eg, on yeast. Therefore brewers seek more efficient means of using hops. Most cone hops in commerce today are therefore further processed to conserve them and to increase the ease and lower the cost of handling them, and to increase utilization of α-acids.

Hops can be milled into a powder, some of the extraneous vegetation removed, and then extruded as pellets and packed under inert gas and vacuum. Unlike cone hops, pellets require cool rather than refrigerated storage and are much more compact and easy to transport. Pellets are used in much the same way as cone hops. To produce isomerized hop pellets, some magnesium oxide is mixed into the powdered hop material before pelletizing and the pellets are kept warm (~50°C) for a few days. These are more easily extracted during kettle boil for increased utilization of the α-acids. Hop pellets can be extracted with solvents to yield syrups that are a very stable and concentrated form of hops. The primary solvent for this is liquid CO_2 though ethanol can also be used. Extracts of hops are used in the wort kettle just as cone hops or pellets might be, but much more conveniently. Extracts, however, can be further modified. By treating the extracts with heat in a mildly alkaline solution the α-acids of the extract can be isomerized to iso-α-acids. Such extracts can be added directly to beer to give bitterness as required, with a high utilization of probably 85% or more. Such syrups can be even further modified. Hop compounds in beer are sensitive to light. This is the reason beer is packaged in dark brown bottles. Light causes the hop compounds to break down to yield a small molecule that, in turn, reacts to yield iso-pentenyl-mercaptan (3-methyl-but-2-enyl-thiol) that has the memorable aroma of skunks. The beer is called “skunky” or “light-struck”. By reacting, the iso-α-acids with a powerful reducing agent under special conditions this reaction can be prevented, and beers containing such reduced-iso-α-acids (eg, rho-iso-α-acids or tetra-hydro-iso-α-acids) can be packaged in flint (clear glass) bottles. The reduced iso-α-acids are somewhat more bitter than iso-α-acids and also remarkably improve the foam stability of beer. The products are quite popular. The iso-α-acids and their reduced forms are also somewhat antimicrobial and help to protect beers from contaminating microbes. It is possible that hops originally became popular with brewers because of their preservative power, but have continued in use because of their desirable taste and aroma impacts.

Hop essential oils, the aromatic component of hops, comprises three groups of compounds in low concentration (0.5–3%, Table 2): (*1*) hydrocarbons, (*2*) an oxidized fraction containing alcohols and esters, and (*3*) a sulfur-containing fraction. The composition of the essential oils is complex and is different in each hop variety; exactly which aroma materials (if any) survive boiling and are responsible for the so-called noble aroma of some beers is not known.

6. Water

Water makes up ~95% by volume of most beers, but the quality of water used in brewing, beyond mere potability, can have an impact on its quality and flavor characteristics. Water contains dissolved ions of which the most relevant to brewing are calcium (Ca^{2+}), magnesium (Mg^{2+}), and bicarbonate (HCO_3^-). The first two represent hardness and the last alkalinity. In general, hardness is desirable for brewing purposes (ie, as a beer component) and alkalinity is not. It is a matter of pH or acidity. The hardness ions lower the pH (ie, make the process somewhat more acidic) during mashing by reacting, eg, with phosphate ions of malt. This promotes enzyme action somewhat. Alkalinity raises the pH. High pH tends to extract harsh materials from malt and hops including astringency and increased color and the beers tend to be less crisp and more satiating and dull. Brewers therefore select brewing water with an hardness/alkalinity ratio suitable to the product they intend to brew, or to treat available water to meet their need. Generally, hard water with low alkalinity is best suited for pale ales, but dark beers such as stouts and porters profit from a certain amount of alkalinity because the extractiveness noted above is desirable in such beers and because roasted malts are somewhat acidic. Lagers are made with quite soft water (relatively low in calcium and magnesium ions) of very low alkalinity.

After sand filtration, chlorination, and carbon filtration to clarify and purify raw water, further treatment of brewing water might be as simple as adding acid to neutralize alkalinity (to the level required), or boiling the (hard) water, which tends to break down the bicarbonate ion to give a deposit of calcium carbonate (a reaction familiar to those living in many hard water areas). Reverse osmosis is a popular modern treatment in which water is forced at high pressure through a membrane. Pure water passes through the membrane and the dissolved ions do not.

The bulk of water used in breweries is for cleaning and sanitizing the plant and for raising steam for transporting energy about the brewery. This is at least 4× the volume of water that goes into the beer and might be as high as 10×. Soft water (ie, lacking Ca^{2+} and Mg^{2+}) is preferred for these purposes because it does not react with cleaners or deposit "stone" on surfaces being cleaned and sludge in steam boilers. The most common cleaners are based on caustic soda or other strongly alkaline agents. Acid cleaning is used about weekly to remove stone that alkaline cleaning can deposit. Also, acid is a useful cleaner in a CO_2 atmosphere (common in brewers' tanks) because the gas does not dissolve in the solution; this is a problem with alkaline cleaners and can cause tanks to implode. After cleaning, the numbers of bacteria on the beer-contact surfaces are reduced further by either hot water/steam or chemical sanitizers based mostly on halogens such as chlorine or iodine. Water leaving the brewery is effluent, the strength of which is measured as BOD (biological oxygen demand) or COD (chemical oxygen demand), pH (acidity), and suspended solids. Brewers minimize these qualities in out-flowing water because they are charged on the composition of it. Some breweries operate pretreatment plants to minimize these charges. Anaerobic treatment of effluent yields a flow of methane as a useful fuel.

7. Other Products

7.1. Adjuncts. Beers can be made entirely with malt, and many are, but much beer is made with a certain proportion of non-malt material (adjuncts). This material is commonly corn (as yellow corn grits) or rice grits or syrups derived from them. These materials are cheaper forms of extract than malt itself, but they provide only starch or (as syrups) hydrolyzed starch, and none of the complex mix of proteins, polyphenols, enzymes, flavor and color compounds present in malt. They therefore dilute malt character and permit the manufacture of delicately flavored beers that are pale in color, crisp, nonsatiating, and easy to drink. Adjunct beers also tend to be more physically stable because they are low in haze-forming materials derived from malt (especially protein and polyphenols).

7.2. Special Malts and Roasted Materials. They have the opposite effect on beer from adjuncts because they are treated in such a way as to enhance their color and flavor impact. They are used at quite low levels of 5 to perhaps 20% in making dark yellow, brown, reddish, and black beers. There are two ranges of products. The first might be called roasted materials because they are ordinary malt that is heated to a higher temperature than normal, in a roasting drum. The higher the temperature used the darker the color of the malt and the more intense its flavor. Roasting with high heat yields black malts. Barley can also be roasted, rather like coffee, to produce a black product. The second range of products is called crystal malts or caramel malts (the use of these words is not exact). These are made from regular malt that is wetted again and "stewed", ie, heated without drying. This causes the interior of the malt kernel to liquefy (the starch hydrolyses by action of amylases), and when the malt is eventually dried and heated the endosperm crystallizes. Malts with a range of colors and flavors different from roasted materials can be made in this way.

8. Brewing

Suppliers deliver the raw materials necessary for beer manufacture to the brewery as needed. Breweries rarely have more than a few day's or a week's supply of materials on hand because storage is expensive in facilities and capital. Malt is generally delivered in rail cars of 70,000-kg capacity or hopper-bottomed road trailers on a daily basis. Barges on canals are an option for transportation in some parts of the world. Extreme cleanliness around the delivery point and silos is necessary to avoid insect infestations and attracting birds and rodents.

A brewery is divided into three main parts: (*1*) the brewhouse where the malt is extracted with hot water to make "wort", (*2*) the cellars where fermentation by yeast takes place and the beer is matured and clarified, and (*3*) the packaging hall.

8.1. Brewhouse. In the brewhouse, the operations are (*1*) milling for crushing the malt, (*2*) mashing for extracting the malt with water, (*3*) filtration to separate spent grain solids from liquid wort, (*4*) kettle-boiling for stabilizing the wort and extracting the hops, and (*5*) wort clarification and cooling. The purpose of the brewhouse is to prepare the malt for extraction by *milling*, produce the extract in *mashing*, recover the extract by filtration (called *lautering/mash filtration*), and stabilize it by *boiling*.

8.2. Milling. For each brew, malt is moved from the silos over a device that computes the weight delivered and enters the mill in a constant stream. The objective of milling is to crush the malt in such a way that the later processes can operate at maximum efficiency. Thus, finely milled malt will be easily extracted, but it will be difficult to separate the liquid (called "wort") from the insoluble material (called "spent grain"). Depending on the filtration device available therefore, the brewer decides on the most suitable milling strategy. Ideally, the endosperm of the malt is reduced to fine particles and the husk remains intact. Almost all mills in North America are dry mills. That is, the malt enters the mill dry and exits as a dry grist. These are roll mills. They might have three pairs of rolls as in a six-roll mill (Fig. 5) although simpler ones are common, especially in small breweries. After the initial crushing rollers, vibrating screens separate the grist particles so that the subsequent rollers crush only particles that need further reduction. In this way, particle size reduction and particle size control is achieved. Wet mills are also used widely around the world. In

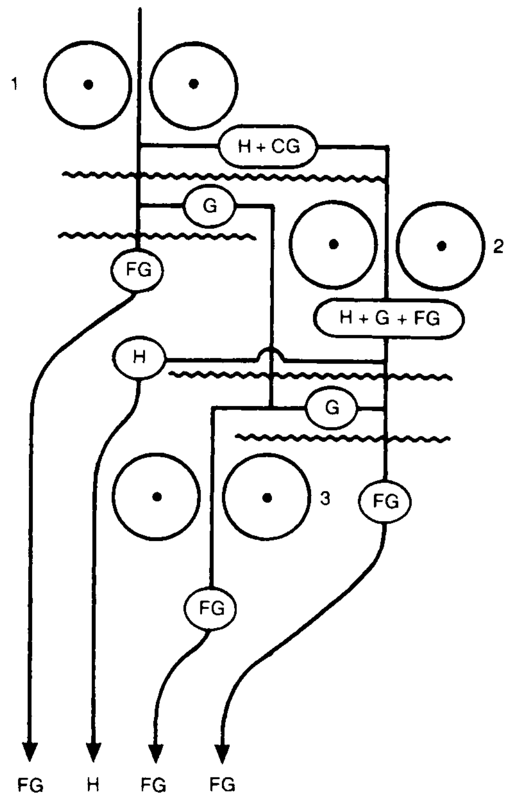

Fig. 5. Schematic of a six roll mill for crushing malt to a desirable spectrum of malt particles. (1) Break rolls; (2) husk rolls; (3) grit rolls, wavy lines indicate the upper and lower shaker boxes for separation of husks and grits (malt particles), H = husks, G = grits, FG = fine grits and flour. two-Roll and four-roll mill designs are alternatives to this, as well as wet-milling. (From Ref. 1, with permission).

such mills, the grain is wetted before passing through a single pair of rolls and exits the mill as a slurry of malt in water that is pumped directly to the mash vessel. Hammer mills that reduce malt almost to a powder can be used with some kinds of mash filters.

Mashing comprises extracting the milled malt with a predetermined volume of water (which establishes mash thickness, but not <2.5–3 hL/100 kg)

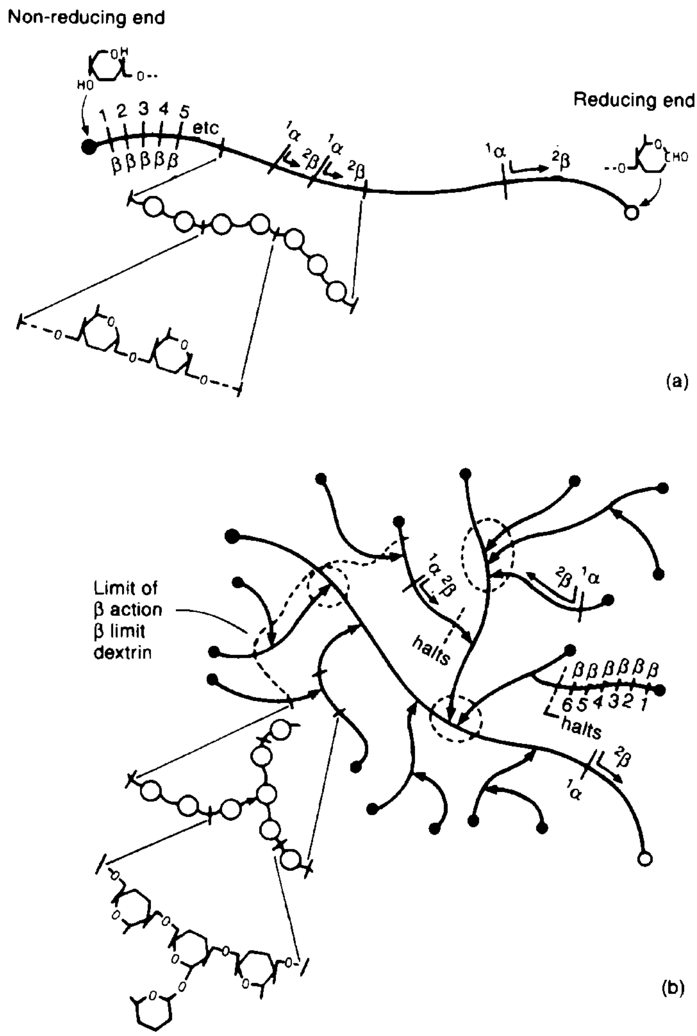

Fig. 6. Attack of α-amylase and β-amylase on (**a**) amylose (25% of total starch) and (**b**) amylopectin (75%), the two components of starch, during mashing, showing the reducing end (open circle) and nonreducing end (closed circle) of the molecules. Small sections are magnified to show the glucose molecules in the straight chain of amylose and at the branch points of amylopectin. Ordered attack by β-amylase (β-1,2,3, etc) from the nonreducing end produces maltose, and, acting alone, would leave a β-limit dextrin of large size from amylopectin. Random attack by α-amylase ($^{1}\alpha$) permits additional attack by β-amylase ($^{2}\beta$). Neither enzyme can attack the branch points of amylopectin (arrowheads) and these survive in beer as glucose polymers called dextrins. (From Ref. 1, with permission).

under closely controlled conditions of temperature, time, and agitation. During mashing the malt enzymes act. Particularly, α- and β-amylase, acting together break down the large amount of starch (a glucose polymer of high molecular weight) present to a mixture of lower molecular weight products (Fig. 6). Roughly 65–70% or more of these products are simple sugars that are fermentable (mostly *maltose*, but also *maltotriose*, *sucrose*, *glucose*, and *fructose*) and the remainder is unfermentable *dextrins*. Preformed soluble materials in malt also dissolve in mashing most importantly amino acids, vitamins, and minerals, as well as the color and flavor compounds of malt. The two amylase enzymes in malt, α- and β-amylase, work together but have different functions. Both break the same bond in starch (the α-1-4 bond between adjacent glucose molecules) but α-amylase is random in action and quite heat stable, whereas β-amylase has an ordered action and is rather heat sensitive. The ordered action of β-amylase produces the large quantity of maltose that appears in wort (this sugar is otherwise rare in nature), and the action of α-amylase opens up the interior of the starch molecule to β-amylase attack (Fig. 6). The α-1-6 bonds of starch survive mashing as dextrins (small glucose polymers) and these, comprising ~30% of the original starch, remain in beer because brewers yeast cannot ferment them.

A note on low-calorie beers. Dextrins (unfermentable residues of starch after the action of malt amylases is complete) contribute calories to beers (about one-third of the total) but little else. By adding enzyme(s) (eg, amyloglucosidase from a bacterium, or enzymes from special malt) to the wort, the dextrins break down to fermentable sugar and are converted to alcohol by yeast during fermentation. Brewers dilute this highly alcoholic beer to yield a beer for sale with a normal content of alcohol and yeast-related flavor compounds but no dextrins, and so with about one-third fewer calories than regular beers. Further calorie savings than this can only be achieved by reducing the alcohol content.

The mashing process in American breweries begins with two separate mashes and is therefore called *double mashing*. The first mash is the *cereal or adjunct mash* (corn or rice) that usually comprises some 25–35% of the total extract (though up to 50% is possible in lower cost beers). Some malt is mixed in with the adjunct to prevent setting, and the mass is slowly brought to a boil and boiled for 20 mins or so (Fig. 7). This gelatinizes the starch so that the malt enzymes can attack it most rapidly. Meanwhile the second mash, the *main malt mash*, is started at ~40°C and after a short period of agitation, the boiling adjunct is blended into the main malt mash. This rapidly raises the temperature to ~65–70°C, and there is very rapid starch breakdown by α- and β-amylase acting together to produce fermentable sugars and unfermentable dextrins. After ~30 mins, the temperature of the mash is finally raised to 75°C or even higher, called the mash-off temperature. Mash-off tends for force the last part of the extract into solution, inactivates enzymes, and reduces the viscosity of the mash. Lower viscosity is useful for the next brewhouse stage, wort separation (mash-filtration or lautering). The total period for mashing is between ~2–3 h depending on the particular product being made.

Brewers can use other mashing regimes and do not need to use adjuncts. For example, traditional ale-making practice in Britain, and in many American microbreweries and brewpubs, requires all-malt mashes and *infusion mashing*.

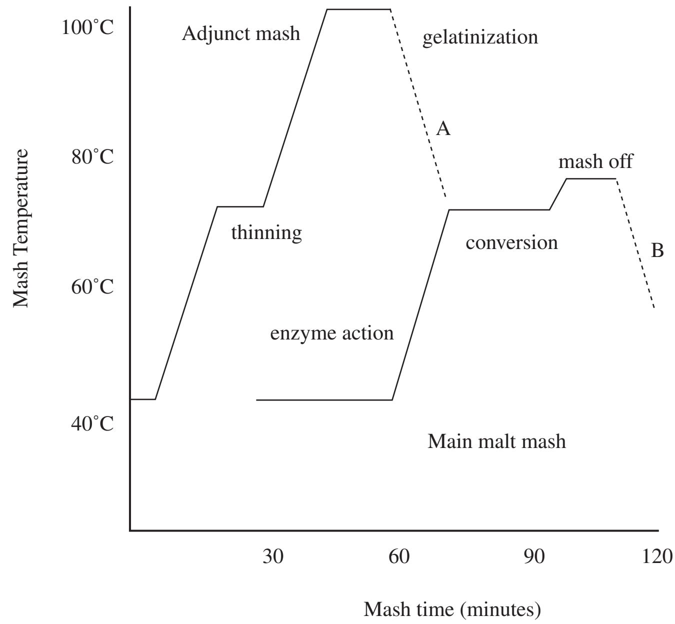

Fig. 7. Temperature profile of a mash using cereal adjunct (eg, rice or corn grits) that must be boiled in the cereal cooker to gelatinize it. The primary event is the hydrolysis of starch to yield fermentable and unfermentable sugars in the main malt mash (during enzyme action/conversion), and the solution of preformed small molecules (such as amino acids), and color and flavor compounds from malt. The dotted lines represent mash transfer: A, boiling adjunct mash into the main malt mash and B, the finished mash to the lauter vessel or mash filter for filtration.

The traditional deep tun (vessel) has a false bottom with slots in it so that mashing and filtration can take place in the same vessel. The cycle time for such a mash is ∼4–6 hs. The malt is mixed with hot water to form a thick mash (∼2.5 L of water/kg of malt) that is held at a single temperature of ∼65°C for an hour or so. Following this, run-off (filtration) of wort begins. *Decoction mashing* is another alternative, traditionally European, mashing regime. This is also usually an all-malt process but (in contrast to infusion mashing) uses a stirred mash with a separate filtration device and a temperature program. In decoction mashing, the temperature program is established by boiling a portion of the malt mash in a small vessel called a mash kettle and returning it to the main malt mash to raise its temperature. In the most traditional forms of this style of mashing, the decoction might be done three times. These days, however, a single decoction is most common.

8.3. Wort Separation. At the end of mashing, the spent grain must be separated from the dense solution (called wort) of sugar and other materials extracted from malt and other grains. This is done by filtration. Two alternative device may be used, a *lauter vessel* or a *mash filter*. The operating principle of both devices is the same. A lauter vessel is a broad flat vessel in which the mash is spread over a false bottom with slots in it. After the mash settles, the wort is drawn slowly through the settled spent grain, where it is clarified, and exits the vessel through the false bottom. In a mash filter, the mash is held in a quite shallow layer against a vertical filter cloth. In either case, the wort, substantially freed of suspended solids, is produced over a period of ~1.5–2 hs and flows to the wort kettle. In both filtration devices, the bed of spent grain is rinsed with fresh hot water to recover as much sugary extract as possible in a process called *sparging*. The spent grain is a brewers' by-product mainly used as animal feed.

8.4. Boiling. Clarified wort from the lauter or mash filter is unstable in several ways: it could possibly contain (*1*) some active enzymes and so be subject to further change, or (*2*) unwanted microorganisms that inevitably find their way to warm moist sugary environments, or (*3*) excessive proteins and polyphenols that could easily cause hazes in beers. By boiling the wort, remnant enzymes are inactivated, bacteria are killed, and much of the protein and polyphenol is precipitated. This precipitate is called "hot trub" or "hot break". In addition, (*4*) the kettle boil concentrates the wort by evaporation of water, (*5*) removes the unwanted volatile components of hops and malt, and, most importantly, (*6*) effects the isomerization of α-acids (which are insoluble in wort and beer) into the bitter and soluble iso-α-acids (Fig. 4). There is also evidence that denaturation (loss of native structure) of proteins during boiling helps form polypeptides that have foam-stabilizing properties.

The wort kettle is a relatively simple device comprising a large (say 500–1500 hL capacity) enclosed insulated vessel with a steam-heated heat-exchange surface called a calandria. The calandria is usually inside the vessel but can be located outside the vessel and the wort pumped through it. Brewers demand a vigorous or "full rolling" boil that is maintained for at least 45–60 min. Hops are added during boiling. Whole (cone) hops, pellets or syrups can be used, or isomerized pellets. The first charge of hops is usually added close to the start of boiling and comprises bittering hops; this is sometimes followed by a middle charge. A third charge is added close to the end of boiling. These are usually aromatic hops that leave some trace of their desirable aroma in the beer.

After boiling, the spent hop material and precipitated trub must be removed. Whole hops, if used, must be removed by a *hop strainer*, but a whirlpool separator best removes the particulate matter from pellets. A whirlpool is a vessel that is about as deep as it is broad; the wort is introduced tangentially so that the wort swirls around the vessel. In this way the particulates quickly settle to the bottom center of the whirlpool where they form a compact sludge pile. Clear hot wort can be run from this vessel to the heat exchangers for *cooling* the wort to a temperature suitable for yeast addition and fermentation. Air or oxygen is gassed into the cool wort stream for yeast nutrition. Upon cooling, a second trub forms called the "cold trub", which can be removed by settlement in a shallow vessel. This concludes the brewhouse processes.

9. Fermentation

Following wort cooling and aeration or oxygenation, yeast is added and the wort–yeast mixture enters the fermentation cellar. Many beer characteristics, especially the alcohol content, are determined by the strength of the wort at the beginning of fermentation. This is expressed as the original specific gravity or O.G., a measure of density. Traditionally the original gravity of wort was 10–12° Plato (°P = % weight/weight (%w/w) or grams of dissolved solids per 100 g of wort. Density is also expressed directly as specific gravity = 1.040–1.048, which is the ratio of the weight of wort to the weight of water). However, these days brewers commonly use *high gravity brewing* throughout the fermentation and finishing processes and then, just before packaging, dilute the beer to sales strength using carbonated water free of oxygen. This practice assures the most efficient use of brewery capacity. In such cases, O.G. might be in the range 15–16° P (common) to 20° P (unusual).

Brewers recover yeast from a completed fermentation to start another, and in this way have nurtured certain yeasts for many centuries. Brewers' yeasts therefore can no longer be found in nature. Brewers have naturally selected yeasts that particularly meet their requirements. Alternatively, one might argue, that certain yeasts behaved in such a way that their recovery was easy. For example, *ale yeast*, when used in small traditional vessels, concentrates at the surface of the fermenting beer where it can be easily recovered by "skimming". Ale yeasts are therefore referred to as "top" yeasts. Because flotation is an unusual behavior, skimming assured the early ale brewers an easy means of recovering a reasonably constant yeast population for reuse. These yeasts are named *Saccharomyces cerevisae*; this designation includes wine yeasts and baker's yeasts, too. *Lager yeast* also has an unusual property that assured the early brewers a reasonably constant yeast supply and a means to recover it: It can grow and ferment at low temperatures and settles readily (bottom yeast). In addition, low temperatures allowed more of the CO_2 evolved in fermentation to remain in solution and so lagers were much more easy to carbonate than ales. Lager yeasts are named *Saccharomyces carlsbergensis* or *Saccharomyces uvarum*. In practice, brewers use lager yeasts at lower temperatures (say 8–14°C) than ale yeasts (say 20°C), and this might well account for the differences in flavor between ales and lagers. Brewers attach great significance to the differences between these two types of yeast, and, indeed, to the nuance of differences among individual strains of these yeasts, because these differences help to define the character of individual beer brands, distinguishing one product from another. Therefore brewers guard their yeast strain(s) jealously, because their yeast strain is a large part of their house flavor character. Nevertheless, the fundamental biochemical differences among ale and lager yeasts are relatively small, and many yeast taxonomists simply call both sorts *S. cerevisae*. Yeasts are fungi (*Saccharomyces* means "sugar fungus") whose growth is primarily unicellular. Brewers' yeasts are spherical to slightly egg-shape and, although the size is quite variable, they are generally large, being some 8–12 μm in diameter (Fig. 8). They increase in cell numbers (grow) by "budding"; in this process a yeast cell grows a small daughter cell attached to it, shares its cell contents and DNA with the daughter, and then splits from it. The split leaves a bud scar on the mother cell. This is asexual reproduction. Brewers recycle yeast from a completed brew to a new one. Some brewers wash this yeast with phosphoric or sulfuric acid at ~pH 2.3 primarily to help reduce the number of contaminating micro-organisms that might accumulate. Nevertheless, yeast recycling is not done indefinitely in modern practice. A batch of yeast might make 8 or 12

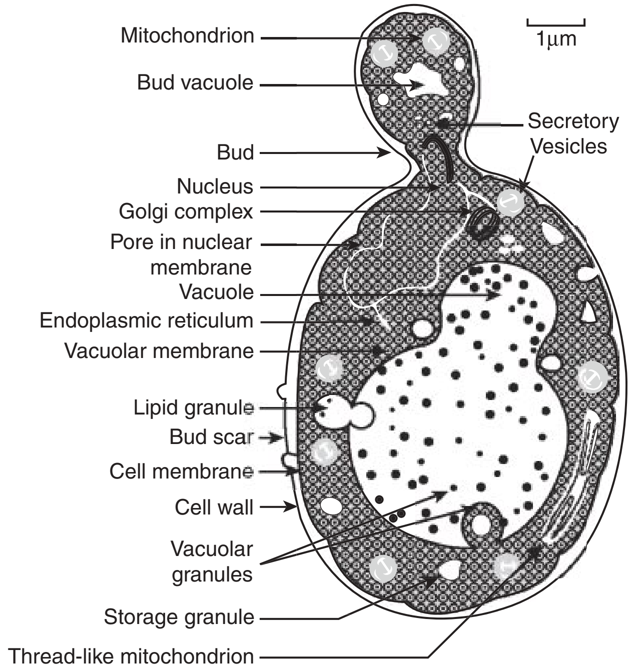

Fig. 8. Schematic of a yeast cell at budding. In fermenting brewers yeast the mitochondria (which are involved in aerobic metabolism) are few and ill-formed. The essential process of fermentation (the Embden-Meyerhof-Parnas pathway or glycolysis) leading to the formation of alcohol and carbon dioxide with the release of some useful biological energy, takes place in the cytoplasm. (From Ref. 2, with permission).

brews and then be discarded (eg, to be used by distillers or for yeast by-products of many kinds) before its performance declines because less vital and even dead cells and bacteria accumulate. New yeast is therefore introduced into the brewery on a regular basis, eg, monthly. This fresh and pure yeast culture is grown in a *propagation plant* (usually located at the headquarters brewery) and distributed to each brewery of a multibrewery company. This helps to keep the product constant at all locations. A modern brewery typically operates with only one yeast strain used as a pure culture. This is considered the best way to assure consistent fermentation.

Yeasts are facultative anaerobes and can grow in the absence of air; ie, they can ferment. When they ferment, however, they are unable to extract much energy from sugar and grow quite poorly compared to aerobic conditions. The main end products of anaerobic yeast metabolism of sugar (2 units) are alcohol (ethanol, 1 unit) and CO_2 (1 unit; much more CO_2 is produced in fermentation than appears in the finished beer), plus some new cell mass and heat ($\sim$140 kcal/kg of sugar fermented) (Fig. 9). In addition, a host of other compounds, each in relatively low concentration, is produced as by-products of anaerobic metabolism and growth; many of these compounds have flavor, and add greatly and positively to the overall flavor impact of beer when in proper proportions (Table 3). Some flavor compounds are less desirable than others; chief among these is a

Table 3. **Types of Chemical Compounds found in Beers and their Approximate Concentration**[a]

Gross composition	Concentration
water	90–95% volume/volume (v/v)
alcohol (ethanol)	2.5–6% v/v (up to 10% in, eg, some barley wines)
carbon dioxide (CO_2)	1.5–3.0 volumes (~2.5–5 g/L)
carbohydrates	2.0–5% w/v (mainly unfermentable dextrins)[b]
calories (kcal/L)	300–900 (mainly from alcohol and carbohydrate)
flavor compounds	
alcohols (other)	100–400 mg/L (mostly amyl alcohols)
organic acids	200–350 mg/L (mostly lactic and succinic acid)
aldehydes	4–10 mg/L (mostly acetadehyde)
esters	10–60 mg/L (mostly ethyl acetate)
lactones, ketones, hydrocarbons	traces
organic sulfur compounds	traces
inorganic volatile sulfur (SO_2)	5–50 mg/L (below 10 in the United States)
hop compounds	10–50 mg/L (mostly iso-α-acids)
other (nutritional)	
vitamin B complex	4–10 mg/L (mostly niacin)[c]
nitrogenous material	0.2–0.6% w/v (as N × 6.25 = protein)
inorganic salts[d]	200–1000 mg/L

[a] Adapted from Ref. 2.
[b] In calorie-reduced beers dextrins can be ansent and alcohol (and calories) lower.
[c] Beer (1 L) can provide 100% of the daily requirement of folate, vitamin B_{12}, and useful proportion of niacin and biotin as well as some calcium, magnesium, and phosphorus. There is no fat, cholesterol or fat-soluble vitamins in beer.
[d] Mainly the cations potassium, calcium, magnesium and the anions phosphate, sulfate, and chloride.

Note: The composition of beers is extremely variable from the lightest to the heaviest beers, and these values are but rought guides. Further, each category of compounds, though dominated by a few substances as shown, can be made up of dozens if not 100 or more components.

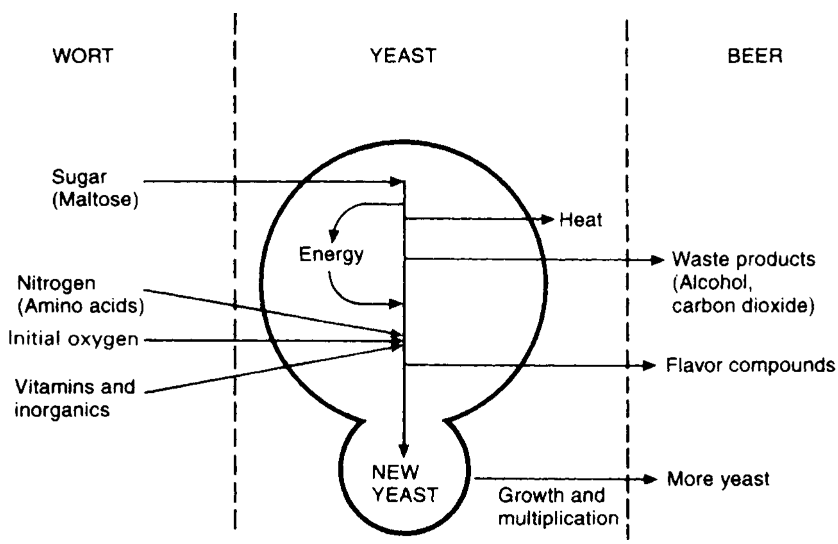

Fig. 9. The main yeast-mediated biochemical events during brewery fermentations. Though maltose (shown) comprises about one-half of the fermentable sugar, glucose, fructose, sucrose, and maltotriose are also present in wort and are fermented. (From Ref. 4, with permission).

compound called diacetyl (2,3-butanedione) that has an aroma like butter, and another is acetaldehyde that suggests a green apple flavor. An important goal of maturation of green beer is the removal or reduction of these compounds.

Of course, yeast cannot grow on sugar alone, and other nutrients derived from malt such as amino acids, vitamins, and minerals, also are necessary for yeast growth. Proper management of (*1*) wort quality in all its aspects, (*2*) yeast amount and vitality, and (*3*) fermentation conditions such as temperature, is necessary to achieve consistent fermentations, and hence consistent beer flavor. Brewers work hard to repeat as exactly as possible wort, yeast, and fermentation conditions from one brew to another to minimize variability. Nevertheless, many individual brews are blended to assure consistent flavor of the final product.

To initiate fermentation, yeast is added to cooled wort in a process called “pitching”. Typically some 10–20 million cells per mL of wort are added (often expressed as 1 million cells/$^\circ$ Plato of wort gravity). Detectors monitor yeast addition to assure this addition is done accurately. As it exits the brewhouse, wort is cooled to $\sim$17–20°C for ale fermentations and 8–10°C for lager fermentations. As a result ale fermentations are shorter ($\sim$3 days) than lager fermentations ($\sim$1 week). Small traditional vessels have now mostly been replaced by large, in some cases, huge vessels. The most imposing are tall, quite narrow *cylindroconical* vessels (ie, vessels with a cylindrical body and a conical bottom) with a working capacity of up to 6000 hL or even more. These are commonplace in modern breweries as they have many advantages. In these vessels, the release of CO_2 bubbles in a rather coherent column rising up the center of the fermenter acts as a stirring device that accelerates fermentation and (later) yeast settlement. The settled yeast is conveniently recovered from the cone of the vessel. These vertical vessels are essentially self-supporting and, if well insulated, do not need to be entirely enclosed in a building. In most breweries, only the cone is inside a protective building because this is where the vessel is filled, emptied, and monitored.

The progress of fermentation is easily measured by the change in specific gravity of the wort as it becomes beer, or the production of alcohol or carbon dioxide. Fermentation is slow at first then, as the yeast begins to grow, becomes much more rapid and the liquid tends to warm up. Alcohol, carbon dioxide, and most flavor compounds are produced roughly in step with yeast growth. Fermentation then slows as the fermentable sugar is exhausted and the yeast begins to fall out of suspension (flocculate). When all the fermentable sugar is used up and there can be no further change in specific gravity, the brewer cools the beer to encourage further yeast settlement. This brings the primary fermentation to an end. The green beer is now ready for the final stages of processing that are designed to (*1*) mature the green beer, (*2*) carbonate it, (*3*) clarify it, and (*4*) render it stable. These processes are *secondary fermentation* and *finishing*.

10. Secondary Fermentation and Finishing

There are three general strategies for maturing the green beer. The first is simply to cool the beer to low temperature (0°C or below) after primary fermentation and hold it for some period of time such as a week or two. This is called *aging*; carbon dioxide can be injected at some stage to achieve carbonation. Second, *krausening* is a widely used secondary fermentation strategy that involves mixing freshly fermenting wort containing yeast into the green beer. This mixture is held at ~8°C for ~3 weeks. During this time, the yeast slowly ferments the added sugar and the carbon dioxide formed is entrapped for carbonation of the beer. At the same time, undesirable flavor compounds such as diacetyl and acetaldehyde are reduced by the yeast action to more or less flavorless compounds. The third strategy of secondary fermentation is called *lagering*. In this process the beer, toward the end of primary fermentation, is cooled somewhat to flocculate much, but not all, of the yeast and is then moved to a new vessel before all the fermentable sugar is exhausted. The yeast ferments out the last few degree of gravity slowly at ~8°C, again with entrapment of CO_2 for carbonation, and reduction of diacetyl and acetaldehyde. A modern maturation strategy that considerably shortens the maturation time for many beers is called the *diacetyl rest*. At the end of the primary fermentation, the beer is simply held at fermentation temperature (~15°C at this stage for lagers, 20°C for ales) until the diacetyl is reduced to specification, as determined by measurement. These secondary fermentation and maturation processes are all time consuming and relatively expensive because the brewery must have many large refrigerated vessels to contain the beer; they are, however, necessary for a quality product.

10.1. Finishing. These processes concern (*1*) *filtration* of the beer at low temperature such as minus 2°C, so that it is brilliantly clear and (*2*) treating the beer with *stabilizing agents* so that it remains brilliantly clear during its sojourn in the market place. Beer is often filtered twice: a rough filtration using diatomaceous earth to remove the vast bulk of the suspended particles and then a polish filtration using, eg, sheet filters to achieve brilliant clarity. Centrifugation sometimes replaces rough filtration, or *finings* (isinglass, ie, specially prepared collagen) can be used to coagulate and settle particles. After rough filtration, stabilizing agents are commonly added. Since the kind of haze most feared by brewers is the protein/polyphenol "chill"-haze (which might arise when the consumer cools the beer before consumption) removing these compounds is a prime strategy for beer stabilization. Modern stabilizing agents are, for the most part, insoluble adsorbents. They include specially prepared silica gels, which remove certain proteins from beer, and/or PVPP (polyvinylpyrrolidone), a compound related in structure to nylon, which removes polyphenols from beer. Beer that has gone through these finishing processes is now mature in flavor, properly carbonated, brilliantly clear and stable against chill-haze formation, and free of oxygen. It is conveyed to a large vessel near the packaging hall called the BBT or *bright beer tank* at which point the brewing process ends. The beer is now ready for packaging and presentation to the consumer.

11. Packaging

Packaging beer into bottles and cans is an immensely expensive process; not only are the packaging materials themselves expensive but the sophisticated machinery, large space required, and numerous skilled employees necessary for packaging add much to the cost. It has been said that if the beer in a bottle or can were replace by water, the price of a six-pack would go down by barely 10%. Two technical factors come into play. First, packaging must be very rapid, ~2000 units/min, eg, so that the large volumes of beer produced by modern breweries can be broken down to consumer units in a reasonably short time. And second, oxygen (air) must be rigorously excluded from the package because it harms beer flavor. With time, especially if warm, the presence of oxygen (even an infinitesimally small amount) in beer causes loss of fresh beer flavor. This is replaced by "oxidized" flavor, often described as a papery or cardboardy flavor, or toasty/bready. For this reason, brewers in North America permit their beers to remain on the supermarket shelf for only ~100–120 days (depending on the market) during which time it retains fresh flavor. Most beers have a "best by" or "born on" date clearly legible to the consumer. Over-age or out-dated beer is withdrawn and destroyed. Imported beers often suffer from these "oxidized" off-flavors because they remain too long in transit to the consumer.

Most beer bottles these days are one-way (nonreturnable) in the United States, though not in other countries. This avoids the environmentally unfriendly practice of sorting and washing returnable bottles, though any overall environmental advantage to one-way bottles does require that they be recycled to the glass plant not merely discarded. New bottles for filling are sanitized, rinsed, and drained and then lifted onto a filling head on a filling machine. Such a machine may have as many as 200 heads (depending on the production required) and is designed as a carousel, ie, it is constantly turning at a speed the eye can barely follow. The filling machine carries a small reservoir of beer that is constantly replenished from the bright beer tank as it is packaged. Each bottle, firmly in contact with each filling head, rides one circuit of the carousel and is then lifted off the machine to be immediately replaced by another bottle. In the short time it is on the machine, the bottle is first evacuated to remove air and flushed with CO_2. This might be repeated. The bottle is then pressurized to the same pressure as is above the beer in the reservoir and then the beer flows down into the bottle slowly at first then more rapidly, by gravity. The fill stops at a preset level and the pressure is slowly released down to atmospheric pressure (the "snift") to avoid excessive overfoaming. The full bottle now moves immediately to the crowner. The bottle is jetted with sterile water to bring up a foam of gas from the beer (CO_2) into the neck of the bottle to displace any air, and the crown is immediately put in place and crimped on. Beer is canned in much the same way except that cans cannot be evacuated to remove air because they would collapse. Beer is packaged in a bewildering variety of bottle and can sizes and shapes to meet consumer expectations and demand. Many special packs are available along with the ubiquitous keg (half-barrel or 15.5 galls United States) for draft dispense, especially in bars and taverns. Plastic (PET = polyethylyethylene terephthalate) packages have been in use in many parts of the world for years but have made little progress in the United States to the present time.

Most beer in bottles or cans is *pasteurized*. That is, the beer is heated briefly to kill any microorganisms that might be present that could spoil beer flavor. As previously noted, no pathogenic (disease causing) organisms can survive in beer. Because brewers assure that the brewing process is extremely sanitary, few microbes enter the beer, and as a result they use a mild heat treatment. A

Table 4. **Production Statistics of Beer**[a]

Country	Population (mill)	Production (m hL)	Imports (m hL)	Exports (m hL)	Consumption (L per head)	draft (%)	Av. Strength (% ABV)
Argentina	36.1	12.4	0.39	0.18	34.9	1	4.8
Australia	18.5	17.5	0.21	0.43	95.0	24	4.3
Austria	8.1	8.8	0.36	0.51	108.1	32	5.1
Belgium[b]	10.6	14.6	0.88	4.9	99.0	40	5.2
Brazil	165.9	88.0	0.26	0.45	52.9	2	
Bulgaria	8.3	3.8	0.013	0.077	45.2	2	4.8
Canada	30.3	22.8	1.17	3.64	67.0	11	5.0
Chile	14.8	3.67	0.14	0.16	24.6	8	4.5
China	1,255.7	196.4	0.33	0.56	15.6	4	
Colombia	38.3	18.3	0.5	0.04	48.9	1	4.2
Croatia	4.5	3.8	0.175	0.523	75.8	7	5.0
Cuba	11.1	1.25	0.046		11.7		5.0
Czech Republic	10.3	18.3	0.154	1.9	160.8	46	4.5
Denmark	5.3	8.1	0.079	2.4	107.7	10	4.6
Finland	5.2	4.7	0.08	0.32	79.1	23	4.6
France	58.7	19.8	5.3	2.4	38.6	26	5.0
Germany	82.0	111.7	2.8	8.4	127.4	20	
Greece	10.4	4.0	0.19	0.3	42.0	5	4.9
Hungary	10.1	7.0	0.18	0.09	70.0	18	4.7
Ireland	3.6	8.5	0.56	3.45	124.2	80	4.1
Italy	57.5	12.2	3.68	0.37	26.9	16	5.1
Japan	126.4	72.2	0.8	0.71	57.2	16	5.0

Korea (Rep)	46.4	14.1	0.011	0.24	29.8	13	4.0
Mexico	95.8	54.8	0.37	7.79	49.4	1	4.0
New Zealand	3.8	3.21	0.181	0.14	84.7	40	4.0
Netherlands	15.7	24.0	0.95	11.7	84.3	31	5.0
Nigeria	106.4	4.2	0.008	0.006	3.9	0	4.5
Norway	4.4	2.2	0.045	0.011	49.7	27	4.5
Peru	24.8	7.2	0.014	0.031	29.0	1	
Philippines	71.4	12.7	0.004	0.092	17.6	1	4.7
Poland	38.7	20.6	0.17	0.12	53.4	21	5.2
Portugal	9.9	6.8	0.29	0.55	65.3	28	5.2
Romania	22.5	9.9	0.06	0.001	44.2	21	4.5
Russia	147.4	32.5	0.73	0.047	22.5		
Slovak Republic	5.4	4.3	0.5	0.46	84	40	4.5
Slovenia	2.0	2.0	0.101	0.433	83.3	13	4.9
South Africa	42.1	25.3	0.42	0.65	59.5	1	5.0
Spain	39.9	25.0	2.0	0.51	66.4	33	5.2
Sweden	8.9	4.6	0.534	0.041	57.3	12	4.0
Switzerland	7.25	3.6	0.72	0.03	59.9	33	4.9
Ukraine	50.5	6.8	0.096	0.06	13.7	36	
UK	59.2	56.7	5.9	3.9	99.4	64	4.1
USA	270.3	235.5	19.1	6.5	83.7	10	4.6
Venezuela	23.2	17.8	0.018	0.49	74.3	1	

[a] From Ref. 3.

[b] Includes Luxembourg, because of inaccuracies introduced by cross-border trading.

pasteurizer is a large tunnel through which the beer cans or bottles move on an endless belt. The containers are sprayed with increasingly hot water to raise their temperature to 60–62°C. They are held at this temperature as long as required, and then cooled by water sprays. One pasteurization unit (PU) is 1 min at 60°C (or its heat equivalent) and most beers are pasteurized in the range of 5–15 PUs. There are two alternative techniques to tunnel pasteurization for dealing with the few microbes that might enter beer. The first is "flash" pasteurization in which the beer before packaging flows through a heat exchanger and is rapidly heated up and cooled down. This minimizes heat damage to the beer, but aseptic (sterile or microbe-free) packaging must follow and that is a challenging and expensive technology. Second, bacteria present can be filtered out of the beer by extremely tight membrane filtration. Again, aseptic packaging must follow this, but advantageously the beer can be marketed as "draft" beer in a bottle or can, because the definition of draft beer (in the United States) is that it be unpasteurized. The bottle is now ready for labeling. The packages are loading into six-pack holders, cased, and enter the warehouse from whence the product is distributed to wholesalers and eventually to consumers.

12. Economic Aspects

Production statistics of beer are listed in Table 4. The United States is the biggest producer of beer although per capita consumption is not high. China is expected to become the biggest producer eventually.

13. Health Value of Beer

Excessive consumption of alcoholic beverages, including beer, is injurious to health, dangerous, and antisocial. However, possible minor nutritional and significant health benefits of beer and other alcoholic beverages are now well documented. When the relationship between all forms of mortality is related to alcohol intake, there is little doubt that moderate daily consumption of alcohol as beer, wine, or spirits, significantly prolongs life, and especially protects against coronary heart disease and stroke among other ailments. Moderate consumption is defined as 1–3 drinks/day. In addition, beer contains some useful levels of B-vitamins (Table 3), especially folate, and some minerals especially calcium, magnesium, potassium, and selenium. Abstention from alcohol on the basis of health alone might therefore be a poor decision.

BIBLIOGRAPHY

" Beer and Brewing" in *ECT* 1st ed., Vol, 2, pp. 382–413, By E. Krabbe and H. Goob, Blatz Brewing Company; in *ECT* 2nd ed., Vol. 3, pp. 297–338, by H. E. Høyrup, the Brewery Association Copenhagen; "Beer" in *ECT* 3rd ed., Vol. 3, pp. 692–735, by H. E. Høyrup, Bryggeriforeningen, Denmark; in *ECT* 4th ed., Vol. 4, pp. 22–63, by J. F. Nissen, The

Denish Brewers' Association; "Beer" in *ECT* (online), posting date: December 4, 2000, by J. F. Nissen, The Danish Brewers' Association.

CITED PUBLICATIONS

1. M. J. Lewis and T. W. Young, *Brewing*, 2nd ed., Kluwer Academic/Plenum Publishers, New York, 2002.
2. G. G. Stewart and I. Russell, *Brewing Science and Technology*, Series lll, Brewers Yeast, Institute and Guild of Brewing, London.
3. C. W. Bamforth, *Tap into the Art and Science of Brewing*, Oxford University Press, New York, 2003.

GENERAL REFERENCES

American Society of Brewing Chemists, *Methods of Analysis*, 8th ed. ASBC, St. Paul, Minn.

S. Baron, *Brewed in America*, Little, Brown. Boston 1962.

D. R. Berry, I. Russell, and G. G. Stewart, eds., *Yeast Biotechnology*, Allen & Unwin, London, Boston.

D. E. Briggs, J. S. Hough, R. Stevens, and T. W. Young, *Malting and Brewing Science*, Vols. I and II, 2nd ed., Chapman and Hall, London, 1982.

D. E. Briggs, *Barley*, Chapman & Hall, London, 1978.

H. M. Broderick, ed., *Beer Packaging*, Master Brewers Association of the Americas, Madison, Wis. 1982.

H. M. Broderick, ed., *The Practical Brewer*, 2nd ed., Master Brewers Association of the Americas, Madison Wis. 1977.

C. Forget, *The Association of Brewers Dictionary of Beer and Brewing*, Brewers Publications, Boulder. Col. 1988.

W. A. Hardwick, ed., *Handbook of Brewing*, Marcel Dekker, New York, 1995.

M. Jackson, *The New World Guide to Beer*, Running Press, Philadelphia, London, 1988.

M. Jackson, *Beer Companion*, Running Press, Philadelphia, London, 1993.

W. Kunze, *Technology Brewing and Malting*, VLB, Berlin, 1996.

H. F. Linskens and J. F. Jackson, eds., *Beer Analysis*, Springer-Verlag, Berlin, 1988.

J. S. Pierce, ed, *Brewing Science and Technology Series I and II*, Institute and Guild of Brewing, London, 1990.

F. G. Priest and I. Campbell, eds., *Brewing Microbiology*, 3rd ed., Kluwer, New York, 2002.

J. R. A. Pollock, *Brewing Science*, Vols. I, II, and III. Academic Press, London, 1979.

A. H. Rose and J. S. Harrison, eds., *The Yeasts*, (4 Vols.) 2nd ed. Van Nostrand Reinhold, New York, 1987.

L. C. Verhagen, ed., *Hops and Hop Products, Manual of Good Practice*, Getranke-Fachverlag Hans Carl, Nurnburg, 1997.

M. Verzele and D. De Keukeleire, *Chemistry and Analysis of Hop and Beer Bitter Acids*, Elsevier, Amsterdam, New York, 1991.

MICHAEL J. LEWIS
University of California