Industrial Beer Manufacturing Process and Quality Control: From Malting to Packaging

Shradha Srivastava, Dr. Preethi Ramchandran, Paras Joshi and Maulana Nur Ardian

Department of Food Technology, College of Agriculture

Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, Uttarakhand, India

***Corresponding Email:** shradhasrivastava0710@gmail.com

Abstract

Beer production is a multistep biochemical process involving mashing, lautering, wort boiling, fermentation, maturation, and packaging. During mashing, malt enzymes such as α-amylase, β-amylase, and proteases convert starch and proteins into fermentable sugars, peptides, and amino acids, influencing yeast activity, flavor, and foam stability. Lautering separates sweet wort from spent grain, while wort boiling with hops ensures sterilization, enzyme inactivation, protein coagulation, and development of bitterness, color, aroma, and flavor (MacWilliam, 1968; Klimczak and Cioch-Skoneczny, 2023). Whirlpooling aids in the removal of trub, producing clear wort. Fermentation using Saccharomyces species converts sugars into ethanol and carbon dioxide, followed by cold maturation to enhance clarity, flavor stability, and ester formation (Nelson and Young, 1986; Eaton, 2006). Packaging includes filtration, pasteurization, and oxygen-controlled filling to maintain quality and shelf life (Bamforth, 2000; Dubey et al., 2017). Moderate beer consumption has been associated with potential health benefits, whereas excessive intake may result in adverse effects (Kaplan et al., 2000; Salanţă et al., 2020b).

Keywords: Brewing Technology, Maturation, Hops, Fermentation

1. Introduction

Beer is the most popular and most consumed alcoholic drink around the world, and it is also one of the oldest. Beer drinking and brewing have been part of human activities since the dawn of civilization. The first beer was basically made from grain, water and spontaneous fermentation due to wild yeast present in the air, just before bread was invented (Campbell, 2017). It has been reported that the Egyptians were the first to document the brewing process around 5000 B.C and the first brewers were part of primitive cultures of Mesopotamia. The birth of modern beer was during the early Middle Ages, when German monks introduced hop as a bittering and flavouring agent. Beer brewing used to be on a domestic scale, but with the arrival of the Industrial revolution, its production moved to mass manufacture, allowing beer to be produced on a much larger scale (Sánchez, 2017).

Brewing is the process in which interaction between water, yeast, starch and hops is done in a controlled manner to obtain the beer as the finished product. During fermentation in yeast cells, glucose is converted into ethyl alcohol (ethanol) and carbon dioxide gas which initiates the formation of beer. The overall chemical reaction is given below:

$$C_6H_{12}O_6 + 2PO_4^{3-} \rightarrow 2C_2H_5OH + 2CO_2 + 2ATP$$

Breweries across the world generally use the system of batch fermentation to produce beer. The fermentation process is carried out inside the brewing yeast cells with the help of a number of enzymes (Campbell, 2017; Gomaa, 2018). Different types of yeast are also used to ferment the beer. The major types of yeast are Saccharomyces cerevisiae and Saccharomyces carlsbergenesis whilst some other important yeast are Saccharomyces pastorianus, Brettanomyces bruxellensis, Saccharomyces uvarum and Torula delbrueckii (Bokulich and Bamforth, 2013; Iorizzo et al., 2021). Brewing contains several steps that involve treating grains, malting, mashing, filtration, and fermentation (Newman and Newman, 2006). In the malting process, green malt or any barley is converted into its stable form and some desired flavouring agents are added due to which beer gets its specific taste and aroma (Linko et al., 1998). Mashing is done to solubilize the grain components by which extraction of starch, sugars, proteins and other products are performed (Osman et al., 2002). During the fermentation process, alcohol is extracted and the carbonation level is established in the beer. At the end of the fermentation process yeast, flocculates can be collected separately.

The production of alcohol is different from other industrial fermentations, because taste, aroma, clarity, colour, foam production, foam stability, alcohol percentage, and saturation are all factors related to the finished product. Beer, ale, porter and stout are examples of malt drinks. Brewing involves microbial activity at all stages, from raw material production to malting in package stability (Bokulich and Bamforth, 2013). This article intends to provide an overview of the industrial beer manufacturing process, focusing on the processing operations and the various types of beer produced.

2. Beer

Beer is a carbonated, fermented alcoholic beverage made by brewing and fermentation from cereals, usually malted barley, as well as maize and flavored with hops, water and yeast and the like for a slightly bitter taste. The manufacturing processes of beer essentially involves treatment of grains, malting or germination, mashing or extraction with water, filtration and fermentation.

There are several types of strains of microorganisms used for the production of beer, such as lactic bacteria and yeast, but the yeast strain Saccharomyces cerevisiae is used as it be found easily and cheaply. During malting, barely kernels are soaked in water and periodically aerated, the so-called steeping and germination phase. Germination process is halted at desired malt quality, green brown malt is converted to stable, storable product, colour and flavor are also developed, enzymes are stabilized and preserved, and unwanted flavours are removed. During germination, three important groups of enzymes are activated: (i) amylases, (ii) proteases/peptidases, and (iii) beta-glucanases. Each of these enzymes have an important function during the malting and downstream brewing process: (i) amylases convert starch, present in the barley kernels, into fermentable sugars; (ii) proteases and peptidases break down proteins and release free amino nitrogen (FAN), while (iii) beta-glucanases degrade the endosperm cell wall, allowing other enzymes access to the endosperm. Next, in the drying and kilning phase, kernels are dried and heated. This stops germination, arrests enzymatic activity within the kernels, reduces spoilage risks, and determines the impact of malt on the final aroma and color of the beer.

Malted barley which, when milled and heated in water to extract its nutrients, provides a nourishing sugar and protein-rich solution named wort (pronounced as wert). It is an ideal medium in which yeast may grow and ferment. In recent times hops is added to the boiling wort as it was discovered that hops had anti -bacterial properties which preserved the wort and fermented beer, giving the beer a refreshing bitter taste (Campbell, 2017). Hops are plants classified as Humulus lupulus which are typical from cold regions and thus require strict cultivation conditions (Almeida, 2020). This plant possesses glands where lupulin granules are produced, which contain brewing's substances of interest such as α-acids and essential oils that are responsible for the typical beer's bitterness and aroma (Kimura, 2021).

The objectives of mashing are solubilization and dissolution of grain components, breakdown of grain cell wall structure extraction and hydrolysis of starch, sugars, proteins and non-starch polysaccharides and fermentable sugar profile is established. These enzymes will hydrolyze starch and other compounds within the kernels during mashing (Goldammer, 2008; Kunze, 2004). During the fermentation, alcohol level is established, flavor profile of beer is established and carbonation level is established. At the end of fermentation, yeast flocculates and can be easily separated. Cold maturation temperatures will influence beer clarity. Using a systematic procedure to solve material balance problems, mass balances in all six steps in this production process were solved (Ore, Mironov and Shootov, 2018).

Beer like any fermented food, is a microbial product. Microbial activity is involved in every step of its production, defining the many characteristics that contribute to final quality. While fermentation of cereal extracts by Saccharomyces is the most important microbial process involved in brewing, a vast array of other microbes affects the complete process (Bokulichn and Bamforth,2013). The flavour and aroma of any beer is, in large part is determined by the yeast strain employed together with the wort composition. In addition, yeast properties such as flocculation, fermentation ability (including the uptake of wort sugars, amino acids, small peptides, and ammonium ions), osmotic pressure, ethanol tolerance, and oxygen requirements have a critical impact on fermentation performance.

For many years the only known method of fermenting beer was a slow batch fermentation process carried out in a single fermentation vessel. This method had disadvantages in economic and quality aspects. The slow fermentation times meant that large numbers of tanks were required to house all the fermenting batches of beer (resulting in high costs of vessels and the associated costs for holding these vessels at the required temperatures and testing the quality of each batch). Recently, continuous fermentation is used which involves recycling part of the fermented beer back to the wort at the start of the fermentation process, the result is a continuous flow of beer out the other end of the process. The wort brewing stage in a continuous system may be carried out at a time appropriate for the brewery. Continuous fermentation employs a system of cold wort storage; the boiled wort is chilled to 0°C (the wort does not freeze at this temperature because of its high sugar content) and held in storage tanks where protein material (which would otherwise make the beer appear cloudy or 'hazy') precipitates out. The wort remains in the storage vessel until it is required to be steadily transferred to the fermentation. One wort storage tank will continuously feed into the fermentation for several days (Campbell, 2017).

2.1. Composition of Beer

The nature and quality of raw materials, their treatment, storage and finishing operations are the main factors that largely determine the constituents present in a particular beer (Hough et al., 1982). Generally, a normal beer includes carbohydrates, peptides or proteins and hop substances such as resins, tannic acid, essential oils, etc. Further, it contains ethanol and carbon dioxide in major proportions with a small percentage of acetic acid and glycerol. Overall, the finished beer usually contains around 85- 92% of water by volume with a pH of 4.1–4.5.

3. Types of Beer

Beer may be categorised into many different types of beers based on the process of fermentation (top/ bottom fermentation), colour (dark/ light), alcohol content (light/

strong), type of additives added, the extracted content and the origin (Wunderlich and Back, 2009). Pilsner refers to a beer light in body and color and contains approximately 3.4 to 3.81 % alcohol. The seasonal Bock beer is brewed in the winter for sale at Easter tune, and the carmalized or roasted malt used in its production provides its dark color, sweet taste, and heavy body. Ale, stout and porter employ top-fermenting yeasts (Eßlinger, 2009). High levels of hops are utilized in ale manufacture, and the alcohol content of the finished product can be as high as 8 % by weight (De Keukeleire, 2000). Stout and Porter employ heavy worts without adjuncts, resulting in a dark-colored, heavy-bodied, high alcohol content beverage.

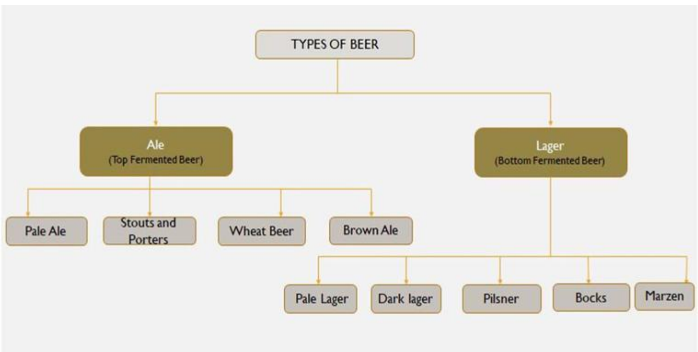

Fig. 1. Types of Beer

Based on the fermentation process, beer is divided into two types: Top-fermented beer and Bottom-fermented beer-

a. Top fermented beer

Ale beer comes under this category in which it gets fermented at a warm temperature (60–70°F) by employing the top fermenting yeasts which are mainly S. cerevisiae (Granato et al., 2011). This beer floats and accumulates at the top of the fermenter tank, resulting in a cloudier beer. Due to their warm temperature and the presence of esters, these beers get fermented in 3–5 weeks. They tend to have a higher alcohol content than lagers. This beer is fully- flavoured and contains some spicy and fruity tones (Polak et al., 2013).

Types of ale beer (Piazzon et al., 2010)

(i) **Pale ale:** It was first produced in England.This beer is made up of hops and malts which contain golden to amber colour and moderate strength. Pale ales bridge the gap between dark stouts and light lagers. They are full of flavours, but not too heavy and are highly approachable.

(ii) **Porter and Stouts:** These beers are fermented at a high temperature. They originated in the UK and are identified by their colour and a hint of molasses-like sweetness. The average thermal conditions are used for brewing stouts. These beers are very dark, almost black ale. This dark colour is developed by roasted barley or by roasted malt, before brewing (Wong, 2003). The taste of this beer is a little bitter or even harsh and have higher alcohol content.

(iii) **Wheat beer:** This beer was originating in Bavaria, Germany. The most widely known wheat beer is Hefeweizen, typically light in colour and sometimes transparent. The taste of this beer is less bitter, making it easy to drink. This may be brewed without hops.

(iv) **Brown ale:** This beer ranges from deep copper to brown. It tastes like chocolate and caramel and is slightly bitter. American-style brown ales have apparent low to medium hop flavour and aroma and medium to high hop bitterness.

b. Bottom fermented beer

Lager beer is the common type of bottom fermented beer that is usually manufactured by ageing in the cold. S. carlsbergensis and S. pastorianus are commonly used for fermented beer (Granato et al., 2011). The yeast gets settled at the bottom of the liquid vessel after fermentation which results in a clear beer. Yeast is more fragile. It needs to ferment more slowly and at a lower temperature than the yeast used in the production of ale beer and it contains a low tolerance to alcohol. Pilsner, Bock, and Marzens are some examples of lager beer (Pavsler and Buiatti, 2009).

Types of lager beer

(i) **Pale lager:** Pale lager has a very light golden colour and it can be found in deep red colour in some circumstances. It contains a low quantity of alcohol and has a light flavour.

(ii) **Dark lager:** This kind of beer is deep in colour. Dark lagers are generally very bitter, but they contain sweet variants that change their taste from stouts or porters. It contains mid-range alcohol.

(iii) **Pilsner:** This beer is brewed in the city of Pilsen, Czech Republic. In this beer, the water used is very hard and it contains a large amount of calcium and magnesium. This beer can sometimes have a floral aroma and is colorless (lighter than that of lager beer).

(iv) **Bocks:** German Bocks are heavy on malty flavour, which makes them sweet and nutty. It contains a low alcohol level, while Doppelbocks, Weizenbock, and Maibocks are the types of bocks that contain high alcohol.

(v) **Marzen:** Marzen beer is also known as “March beer”. It is a golden to deep amber lager style and it is bitter in taste. These March beers were usually brewed slightly stronger than regular beers and they were stored in cool areas so, that they could keep better.

4. Components for Beer Production

The medium for beer production generally contains carbon and nitrogen substrates along with various vitamins, growth factors, metal ions and so forth for yeast (De

Keukeleire, 2000). In addition, the medium must contain the components that contribute to the desired aroma, flavor, foam characteristics, color, clarity, and stability characteristics of the finished beer. One most important factors that should be kept in mind while designing the media components for beer production is that yeast is not able to directly utilize certain nutrients of the medium. For instance, the primary carbon source of the medium is starch, however, yeasts cannot utilize its carbon. To preclude this problem, starch has to be degraded to maltose and glucose by the action of the enzyme malt amylases (Maicas, 2020).

This enzymatic reaction, in turn, forms dextrins (partial degradation products of the starch) in addition to maltose and glucose. Intriguingly, the produced dextrins are not utilized by the yeast, but they are important, due to their association with the flavor of the product. Apart from this, the nitrogen source of the medium i.e., proteins, cannot utilized by yeast as the yeast does not possess proteolytic activity (Gomaa, 2018). Associatedly, a portion of the protein must be partially degraded to peptones and larger peptides as they contribute flavor and foam characteristics to the final product (Westermann and Huige, 1979). On the whole, the partial and total degradations of both the carbon and nitrogen substrates of the medium are accomplished by employing the amylase and protease enzymes, respectively, of malt as prepared from barley. Notingly, the malt, in addition to these enzymes, also provides protein nitrogen compounds and, in most instances, part to all of the starch of the medium, although some of the starch may be supplied by "malt adjuncts."

4.1. Raw Ingredients of Beer

The main ingredients of beer are water, starch sources like malted barley, fermented yeast which converts glucose into alcohol and a flavouring agent like hops (Humulus lupulus) (Humia et al., 2019; Carvalho et al., 2023).

Water

Water is the main raw material used for brewing, representing around 94% of a beer's weight (Puncocharova, 2019). The term "malt" defines the material that results from germination, under controlled conditions, of any cereal (e.g., barley, rice, corn, wheat etc.) (Ambindei, 2022). Among many other compounds, malt contains three highly valuable constituents from a brewer's perspective: starch, proteins and hydrolytic enzymes. Starch is the major source of carbohydrates in beer's wort and is hydrolyzed by enzymes (i.e., amylases) to convert it into fermentable sugars, which in turn determine the alcoholic content of the final beer product (Yin Tan, 2021). Moreover, other hydrolytic enzymes (i.e., proteases) convert a fraction of proteins into amino acids that are essential for yeast's nutrition during fermentation, and the remaining intact fraction of proteins are responsible for beer foam properties (Yang, Gao, 2020).

The composition of the water is of extreme importance as it affects flavor and other properties of the beer. The bicarbonate ions as a dissolved mineral contribute to the finished beer's taste. Water in the beer must be free from any organic or inorganic pollutants or any undesirable products such as bacteria, sediments, etc. Water is necessary for brewing as well as for maintaining the cleaning. Different regions contain different qualities of water which are suitable for the production of different beers, for example, Dublin has hard water which is well suited for making Stouts whereas in the Plzen region, soft water is present which is best suited for making Pilsner.

In brewing water is distinguished by contents and salt concentration. Modern technologies allow brewers to regulate the concentration of salts in water with a very high level of accuracy.The characteristics of good water for brewing are a pH of 6.5 to 7, less than 100 ppm calcium and magnesium carbonates, trace amounts of magnesium (preferably as the sulfate), 250 to 500 ppm calcium sulfate, 200 to 300 ppm sodium chloride, and 1 ppm or less of iron (Zambrzycka-Szelewa et al., 2020).

Malt

It is a product obtained from the germination of grain seeds. In order to produce beer, barley is used which passes malting – a process that facilitates the germination of grain. After soaking barley seeds swell and chemical reactions start which causes starch-splitting to obtain malt sugar required for fermentation. Other crops like wheat, rye, triticale, spelt, and emmer are also suitable for brewing. Mostly they are added to barley malt.

Starch source in beer which, when milled and heated in water to extract its nutrients, provides an ideal fermentable medium (consisting of nourishing sugar- and protein-rich solution named wort) in which yeast may grow and ferment. The malt contributes amylases, proteases, starch, protein, additional yeast nutrients and growth factors, and flavor characteristics to the medium. Before use, malt is treated to make it suitable for use. This process of preparation of malt is called the malting process (Cadenas et al., 2021).

In steeping ,barley grains are transferred to cold water (12–15°C) and soaked in it for 2–3 days followed by regular replacement at every 10–15 h. Meanwhile, the process of aeration is done to activate the barley grains by increasing their respiration rate (Schwarz and Li, 2011). Lastly, but importantly the excess amount of water is finally drained from the soaked barley. Subsequently, in the next stage called germination, the grains are incubated for 4–6 days periods approximately with 45 % moisture to allow the formation of a short rootlet. This, in turn, will help the formation of highly active α-amylase, β-amylase, and proteolytic enzymes, as well as various flavor and color components. At the end of the incubation period, the germination is stopped by raising the temperature just high enough to stop all biological activities without harming the desired enzymes (below 50°C). This process is called Kilning. Analogously, roasting at higher temperatures is employed at this point to obtain darker-colored carmalized malts (with reduced enzyme activity) for stout and bock beer fermentations. The "green malt" produced at the end is carefully dried and stored. Finally, the rootlets of culms are removed to get malt ready to use in the brewing process (Parker, 2012; Gomaa, 2018).

The grain malt is the key material that determines the flavor and strength of the beer; hence different types of grain can produce beer with differentiating flavors. Wheat malt has more protein and gives a more foamy head with a fuller taste. On the other hand, corn malt brings lighter beer with decreased haziness and enhanced flavors, thus giving more neutral sweetness to the beer.

Yeast

Yeasts are unicellular fungi that proliferate by consuming sugar which is responsible for beer fermentation. During the fermentation process, yeast consumes sugar which produces ethanol and CO2 as gas. Moreover, in the fermentation process, yeast also adds some aromatic substances which give the beer a unique characteristic. Different types of yeast are used for fermented beer like S. cerevisiae a top-fermented yeast whilst S. carlsbergenesis and S. uvarum are bottom-fermented yeast. Some other yeasts are also employed like B. bruxellensis, T. delbrueckii etc (Iorizzo et al., 2021; Carvalho et al., 2023).

The microorganism used for the fermentation of the wort produced in beer production. Yeast family Saccharomycetaceae is favored as brewer's special yeast. Two dominant types of yeast fermentation methods are widely used for beer manufacturing: top fermentation and bottom fermentation. In the top fermentation technique, the yeast extract is layered on the surface of the malt. The most favored yeast organism for this technique is *Saccharomyces cerevisiae,* which is cultivated at 15-26 degree Celsius and are found in such kinds of beer as porter, ale and stout. In bottom-fermenting, the yeast extract is layered at the bottom of the beer must. *Saccharomyces pastorianus* is the yeast organism used in bottom-fermenting, which is cultivated at 8-14 degrees Celsius and are used in the production of lager and Central European beer. The difference between these types of brewer's yeasts is in that the final stage of fermentation top fermentation yeast are gathered on the surface (float up) and bottom-fermented – at the bottom of the beer must. This significantly affects the taste.

The following are the main criteria for a good brewing yeast: fermentation behavior (bottom or top fermentation), flocculation (powdery or flocculent yeast), fermentation performance (fermentation rate, degree of fermentation), production, and degradation of side products (aroma development, diacetyl removal), as well as intensity of propagation.

Hops

Hops is a dioecious perennial herb that belongs to the family Hamemmelidae. It bears two flowers staminate and pistillate. Hops are the dried female flowers of the hop plant. Only pistillate flowers (made up of leaflets) that have cone like appearance have brewing value (De Keukeleire, 2000; Damjanović and Varga, 2021). Under these small leaflets yellow glands and lupilin is present which contains resin and aromatic essential oils. During the production of beer, lupulin is converted into its bioactive form humulone and lupulone (Gerhäuser, 2005; Čeh et al., 2007). All these contribute to aromatic, refreshing bitter characters, retention of foam and stabilizing effect through increases in the shelf life of beer (De Keukeleire, 2000; Damjanović and Varga, 2021).

The hops also provide tannin substances that combine with protein to form insoluble flocs. Apart from that, the tannic substance in hops plays the role of preservative (due to anti-bacterial properties) and natural clarifier of the fermented beer. Some pectin is also extracted from hops, and it may be involved in the formation of foam of the finished product. It gives the beer a distinctive bitter taste and fragrant aroma.

Three groups of substances are interesting: hop resins, flavoring agents, and polyphenols. Hop resins constitute about 10–20% of the hop dry weight. Their important components are the α- and β-acids, whose bittering potential differs markedly. α-Acids are transformed into iso-α-acids during boiling. These iso-α-acids and their derivates have significant bittering potential. β-Acids have a low solubility in wort and beer. Thus, they contribute only a little to bitterness. Hop resins enhance physiological digestibility, foam stability, and bacteriostatic nature of wort and beer over and above the bittering potential. Hop possesses approximately 0.4–2.0% flavoring agents per dry weight. These are essential oils that are responsible for the hop aroma and bouquet. Polyphenols (4–14% hop dry weight) also impact on beer quality. Additionally, low molecular polyphenols show antioxidative properties. The hop polyphenol xanthohumol has been identified as a possible anticarcinogenic agent.

5. Brewing Process

The process of making beer is known as brewing and a dedicated building for the commercial making of beer is called a brewery. The main purpose of brewing is to convert starch source into a sugary liquid which is known as wort (a liquid rich in sugars, nitrogenous compounds, sulphur compounds and trace elements extracted from malted barley) and to convert that wort into an alcoholic beverage with the help of the controlled fermentation process (Bokulich and Bamforth, 2013). The fermentation process is done in closed vessels and sometimes secondary fermentation also takes place in the brewery, in the cask, or the bottle.

Brewing is a huge-scale complex process that transforms water, grains and hop into beer with the help of yeast. Basically the large variety of beer is due to the different conditions (temperature, kind of grain, etc.) established during the stages of production (Sánchez, 2017). The body of the beer is provided by barley, more specifically barley malt and in general, a few hundreds of grams are used for one litre of beer. The malt may be partly substituted by starch-rich adjuncts such as rice, corn or wheat.

During brewing, a slurry of barley malt and brewing water (called 'mash') is heated around 60˚C, the malt enzymes, mainly amylases but also proteases, degrade starch and proteins, leading to a mixture of sugars and peptides or amino acids. For that purpose, barley must be subjected to a controlled germination, during which these enzymes are formed in the barley grain prior to mashing. Such germinated barley is known as barley malt. (Keukeleire,2000). The starch-to-sugar conversion is stopped by heating. Depending on the conditions (time, temperature), pale or amber-coloured or even dark malts are obtained, the colour being due to caramelization of sugars. It is important to notice that the colour of beer is derived from the colour of the malt(s) used. Furthermore, it is obvious that coloured malts exhibited a distinct taste, which often is characteristic of particular dark beers. After filtration, the sugar solution in brewers' jargon called 'wort' is transferred to the brewing kettle, where it is boiled during at least one hour with the addition of hops (Humulus lupulus L.). The amount of hops needed is only a fraction of the substantial quantities of malt used in the brewery. Besides the formation of insoluble complexes with proteins and polypeptides (contributing to the stability of beer) hops sterilize the wort solution. The most important asset of hops is the bitter taste conferred to, particularly blond beers. Furthermore, hops are necessary for the stabilization of beer foam (Keukeleire, 2000).

After cooling and removal of spent hops, the liquid known as 'hopped wort' is pumped to the fermentation vessels and yeast is added under aeration for growth. During the anaerobic phase yeast cells convert sugars to ethanol and carbon dioxide. Depending on the temperature during fermentation and the nature of yeast collection at the end of the fermentation period, beers are distinguished as being produced by 'bottom fermentation' or 'top fermentation'. When the activity stops, the yeast cells collect to the top as a dense foam (Keukeleire, 2000) A typical fermentation takes about one week thereby delivering a so-called 'green beer' or 'young beer' which is not drinkable, as a number of offending (bad taste and smell) compounds are formed during fermentation. Consequently, beers need a maturation or lagering period of several weeks at about 0˚C, during which the unwanted components are slowly decomposed. Only after the content has decreased below critical values can beer be packaged. For prolonged conservation beers may be pasteurized. Special beers often require a slow (several months) second fermentation, usually in oak kegs, to generate sour flavours. (Keukeleire, 2000).

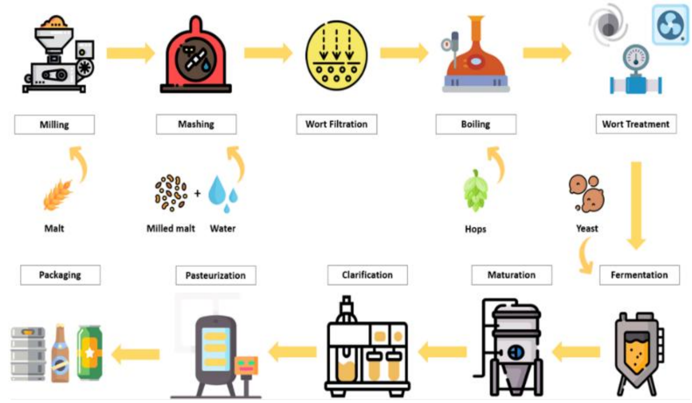

Fig. 2. Schematic diagram of the brewing process and the involved raw materials. The icons used in this figure were retrieved from Flaticon.com

Malting & Milling

Beer is produced from barley grains, which are first modified into malt by the maltster and milled immediately prior to use. Each beer has its own formulation with respect to the blend of different malts used. For conventional beers, the protein content of barley grains should be between 11 and 11.5%. Barley with higher protein content can lead to colloidal instability in beer. Malting grains of different sizes results in heterogeneous malt, as smaller grains possess higher protein content and germinate faster than larger grains. Such heterogeneous malt can cause processing problems and ultimately reduce beer quality.

Malting is defined as the artificially induced germination of a crop. The malting process involves steeping, germination, drying, and curing of malt.

Steeping

The malting process begins with steeping, where barley is immersed in water. Barley is harvested at a moisture content of approximately 12% and steeped in water at a temperature of 12–15°C for 40–50 hours. During steeping, the grain absorbs water, resulting in a volume increase of about 25%, and the moisture content rises to approximately 45%. Barley grains possess a white root sheath known as the chit, which breaks through the husk during steeping. After this stage, the chitted barley is removed from the steep, drained, and allowed air rests before germination.

Germination

Germination requires sufficient heat, oxygen, and humidity. The temperature range for germination lies between 14°C and 18°C. Oxygen is essential for respiration, and carbon dioxide must be removed to prevent embryo death. Traditionally, steeped grains are placed in heaps for 24 hours and then spread onto floors for germination. During this stage, embryo development becomes visible at the root germ and acrospire. Germination leads to the formation of highly active α-amylase, β-amylase, and protease enzymes, along with various flavor and color components. These enzymes degrade reserve substances, converting complex sugars such as glucans and insoluble proteins into soluble sugars and amino acids within the endosperm. Six days is considered the optimum duration for steeping and germination.

Kilning of Malt

Kilning is carried out to remove water, fix substantial transformations, and develop typical malt color and aroma. Drying green malt removes moisture and arrests approximately 30–40% of enzyme activity. Kilning is subdivided into two phases: withering and curing.

During withering, water content is reduced from approximately 45% to 10% at low temperatures. Curing is performed at temperatures ranging from 80°C to 105°C. Higher curing temperatures, particularly around 95°C, result in darker malt color and a characteristic dark malt aroma due to reduced dimethyl sulfite content. For pale malts, curing temperatures are maintained between 76°C and 80°C to preserve enzymatic activity.

Several chemical and enzymatic transformations occur during kilning. At temperatures below 40°C and water content above 20%, the process is referred to as the growing phase, where enzymes cause dissolution of the grain and increase degradation products. At temperatures between 40°C and 70°C, further enzymatic degradation occurs, known as the enzymatic phase. As water content decreases, degradation processes stop, embryo growth is discontinued, and degradation products accumulate. Higher kilning temperatures result in darker beer. Radicles are removed after kilning, as they rapidly absorb water, contribute to bitterness, and increase beer coloring.

Milling

Prior to mashing, malt must be milled. Milling involves crushing dried barley grains between rollers to produce a coarse powder known as grist. Milling increases the reactive surface area for enzymes, making malt ingredients easier to dissolve. Malt can also be finely milled using a hammer mill. The quality of milling directly affects mashing and lautering and therefore influences the quality of the final beer. Poorly dissolved malt requires finer milling to facilitate physical and enzymatic degradation, whereas well-dissolved malt can be milled more coarsely.

Mashing & Lautering

Mashing is the process in which milled malt (grist) is mixed with hot water to allow enzymatic conversion of starch into sugars, forming a fermentation medium known as wort. The mash is prepared in a special container called a mash tun, which is equipped with a mixing paddle to ensure constant agitation of the water–malt mixture. Steam jackets fitted to the outside of the tank allow heating of the mash in stages. The entire mashing process generally takes about two hours.

The temperature of the mash is crucial, as sugar formation is temperature dependent. Some sugars formed during mashing are fermentable, while others are non-fermentable and contribute to the richness and mouthfeel of the finished beer. Grist is typically mixed with warm water and maintained between 62–70°C for approximately one hour. During this period, starch is hydrolyzed into fermentable sugars by amylase enzymes, and proteins are broken down into smaller peptides and amino acids by proteolytic enzymes. The degree of enzymatic hydrolysis is strongly dependent on both temperature and pH.

In some brewing methods, adjuncts are added to water together with milled malt in a ratio of approximately two-thirds malt to one-third adjuncts. These adjuncts are boiled beforehand to gelatinize their starch. The mixture then undergoes mashing, during which malt enzymes are allowed to act at different temperature rests. After completion of mashing, the wort is separated from protein debris and undissolved husks and subsequently boiled with hops (Dewar et al., 1997).

Enzymatic Reactions During Mashing

The malt's amylolytic and proteolytic activities operate within specific temperature ranges. Temperatures around 50°C favor the formation of amino acids and low-molecular-weight peptides, whereas temperatures near 60°C promote the production of higher molecular weight peptones and peptides. Since yeasts lack proteolytic enzymes, protein breakdown products formed at lower temperatures are essential for yeast growth (Taylor, 1992; Gomaa, 2018). The optimum temperature range for malt α-amylase and β-amylase activity lies between 57°C and 77°C (Gomaa, 2018).

Starch consists of two polysaccharides: amylose and amylopectin. Amylose is a linear glucose polymer, whereas amylopectin contains numerous branched chains. β-amylase acts on the non-reducing ends of linear chains and can only hydrolyze straight chains, functioning optimally between 57 and 65°C. Its activity stops at the branching points of amylopectin. α-amylase, with an optimum temperature range of 70–75°C, cleaves starch randomly, producing large dextrin fragments and exposing linear chains for β-amylase action. Dextrins are further broken down slowly by α-amylase. Some straight and branched fragments of amylopectin resist enzymatic degradation and remain as non-fermentable dextrins, contributing to beer body (Olaniran et al., 2011; De Schepper et al., 2021).

Amylolysis

Amylolysis occurs in three main stages:

→ **Gelatinization –** Starch molecules absorb water, swell, and gelatinize at approximately 60°C in the presence of amylases.

→ **Liquefaction –** Gelatinized starch is digested by α-amylase through cleavage of α-1,4 bonds, reducing viscosity and creating new substrates for β-amylase.

→ **Saccharification –** Dextrins are further reduced to maltose and other fermentable sugars.

Different starch sources such as rice, corn, rye, and sorghum possess different gelatinization temperatures compared to malt starch.

Proteolysis

Proteolysis refers to the breakdown of proteins into peptides and amino acids and is carried out by endo- and exo-peptidases. Endopeptidases cleave protein chains internally, increasing soluble nitrogen content, while exopeptidases act at the ends of protein chains, releasing free amino acids. Protein degradation is most pronounced around 50°C. Medium- and high-molecular-weight degradation products formed at 60–70°C are important for flavor development and foam stability. Some proteins precipitate during mashing due to changes in temperature and pH.

Cytolysis

Cytolysis involves the degradation of hemicelluloses present in the cell wall. Breakdown products dissolve and initially increase mash viscosity. The main degradation occurs below 50°C and decreases rapidly as temperature increases. β-glucan degradation ceases between 60–70°C. Most lipids remain insoluble and are removed with spent grist.

Mash Preparation and Wort Formation

Mash preparation involves adding sufficient water (approximately 3–4 hl/kg malt) to accelerate enzymatic reactions. A commonly used method is the high-short mashing procedure, in which the mash is held at 60–63°C for 30–45 minutes and then heated at a rate of 1°C per minute to 72°C. This temperature is maintained until iodine normality is achieved, indicating complete starch breakdown. The liquid obtained after mashing is known as wort and contains approximately 10% sugars along with other organic compounds such as carbohydrates and proteins.

Lautering

Lautering is the process of separating liquid wort from the solid spent grist. This separation takes place in a vessel known as a lauter tun, where grain husks act as a natural filter bed. The first wort drained has an extract content of approximately 16–20%, while subsequent sparging with hot water produces last runnings with an extract concentration of about 0.5–1% (Callejo et al., 2019).

Temperature plays a critical role during lautering, as higher temperatures reduce viscosity and accelerate the process. However, temperatures above 80°C are unfavorable because α-amylase becomes inactivated, preventing further saccharification of residual starch. Typically, the mash is allowed to rest in the lauter tun to form a stable grain bed. The initial runoff containing suspended particles is recirculated, after which wort is collected while sparge water is added either continuously or stepwise.

Modern breweries may use mash filters with polypropylene filter sheets, allowing finer milling of grain. Continuous sparging is commonly employed, and second or third runnings may be collected separately, producing progressively weaker wort and beer. This method is known as parti-gyle brewing (Kühbeck et al., 2006).

Boiling & Whirlpool

Once lautering is complete, the clarified wort is transferred to the kettle, traditionally a copper vessel, where it is boiled for 60–90 minutes. Wort boiling ensures sterility, halts enzymatic activity from mashing, and evaporates excess water, thereby concentrating the wort and slightly intensifying its colour. Boiling also partially caramelizes sugars and removes unstable substances that could otherwise precipitate later in the brewing process or in the final product (MacWilliam, 1968; O'Rourke, 2002).

Hops are added during wort boiling, initially at the start of the boil to impart bitterness and later towards the end of the boil to enhance aroma and flavour (Klimczak and Cioch-Skoneczny, 2023). Only a small quantity of hops is required during this stage. Wort boiling facilitates the extraction of hop components such as tannins, essential oils, bitter acids, and resins. The bitter acids humulon and lupulon contribute to beer bitterness and possess antibacterial properties, with humulon exhibiting stronger bitter flavour and antiseptic activity. Although essential oils are volatile and largely evaporate during boiling, late hop additions help retain aroma in the wort. Overextraction of hops, however, may lead to excessive and undesirable bitterness (Klimczak and Cioch-Skoneczny, 2023).

Tannins derived from hops assist in the coagulation of extraneous proteins, protecting the wort from contamination by Gram-positive bacteria during fermentation. As temperature decreases, complexes formed between negatively charged tannins and positively charged proteins become less soluble, aiding in the formation of froth and contributing to the characteristic bitter flavour and aroma of beer. The boiling process also coagulates residual and partially hydrolyzed proteins originating from mashing, which, if left untreated, could result in turbidity in the finished beer.

During boiling, a flocculent precipitate known as "hot break" or "hot trub," composed of coagulated proteins and hop particles, is formed. These precipitates must be removed after boiling. In some brewing systems, a special straining vessel known as a hop back is used to eliminate residual hop matter. Removal of hot trub is essential to obtain a clear wort and to improve beer stability (MacWilliam, 1968; O'Rourke, 2002).

After boiling, the wort is subjected to whirlpooling. In this step, the liquid is stirred using a pump or spoon to create a whirlpool effect. Centrifugal forces cause solid particles to aggregate at the center of the vortex, while clarified liquid moves toward the periphery. The solid material collected during this process is referred to as trub (Schisler et al., 1982). Partial removal of trub from the bottom of the kettle ensures that the bitter wort remains clear before transfer to the next stage.

Following whirlpool separation, the wort must be cooled as rapidly as possible to minimize the risk of microbial contamination. Cooling temperatures depend on the fermentation type, with 5–10°C required for bottom fermentation and 15–25°C for top fermentation. At this point, the wort is fully prepared for fermentation, having undergone sterilization, clarification, concentration, flavour development, and enzyme inactivation during boiling and whirlpooling.

Cooling Through Heat Exchanger

Once boiling is complete, the wort is cooled to around 20 ˚C through a heat exchanger on its way to the fermenter. This process takes about 1 hour. By heat exchanging, we recover the energy used to boil the wort, i.e. cold water becomes hot water, and returned to the Hot Liquor Tank which is then used to brew more beer or for cleaning.

Fermentation & Maturation

Once the cooled and aerated wort is transferred to the fermentation tank, yeast is added to initiate fermentation. Yeast ferments the wort and converts it into beer. Beer fermentation is a naturally variable process influenced by the composition of raw materials and the characteristics of the yeast strain used. Closed fermentation systems are more commonly employed than open fermentation, as they allow better control of contamination by unwanted yeasts and bacteria. Fermentation temperature and duration depend on the type of beer and yeast strain, resulting in variations even among batches of similar quality (Kaneda et al., 1992; Siebert, 2001).

Fermentation is typically carried out in closed fermentation tanks equipped with cooling coils after the wort has been aerated and chilled to approximately 10–11°C. Primary fermentation usually takes 3–4 days, although total fermentation may extend up to 14 days depending on conditions. Lager beers are generally fermented below 16°C, whereas ales are fermented at temperatures above 20°C. Within 24 hours of yeast pitching, foam formation begins on the surface of the wort, initially along the tank walls and later spreading across the surface. Increased carbon dioxide evolution causes yeast cells to remain suspended in the medium.

During fermentation, the yeast undergoes rapid multiplication, producing ethanol and carbon dioxide, along with small amounts of glycerol and acetic acid. The peak metabolic activity occurs between 40 and 60 hours after pitching, during which significant heat is generated, raising the fermentation temperature to approximately 12–13°C. Carbon dioxide evolution reaches a maximum around the fifth day of fermentation. By days 7–9, carbon dioxide evolution ceases as yeast cells become inactive, flocculate, and settle. Yeast is often harvested from the cone section at the bottom of the fermenter for reuse in subsequent fermentations.

In some brewing practices, the fermenting wort is transferred to a secondary fermentation tank to remove weakened or dead yeast cells, precipitated proteins, and undissolved hop resins that accumulate as sediment in the primary tank or within the foam layer. Additional aeration may facilitate this separation. However, this transfer may not be necessary if the boiled and cooled wort has been adequately filtered prior to fermentation (Pilkington et al., 1998). Toward the end of fermentation, surface foam collapses as carbon dioxide production declines, and some surface scum may be removed to improve flavour quality (Pilkington et al., 1998; Solgajová et al., 2013). Most beers produced contain an alcohol content of approximately 3.5–5%.

Fermentation is carried out using specific yeast strains, with Saccharomyces pastorianus and Saccharomyces carlsbergensis functioning as bottom-fermenting yeasts and Saccharomyces cerevisiae as a top-fermenting yeast. Yeast inoculum is commonly recovered from previous fermentation batches and treated with tartaric acid, phosphoric acid, or ammonium persulphate to reduce pH and eliminate bacterial contamination. Yeast is typically added at a rate of approximately 0.3 kg per hectolitre of wort. Closed fermenter tanks are preferred, as the carbon dioxide liberated during fermentation can be collected and reused during carbonation.

Maturation and Carbonation

The beer obtained after fermentation, referred to as green or young beer, is not yet suitable for consumption and requires maturation. The beer is chilled gradually to 10°C and then to 4°C and stored for maturation, usually for about three weeks. In cold-storage maturation, the beer is held between 0 and 3°C for periods ranging from several days to several months. During this time, yeast cells, resins, proteins, insoluble phosphates, and other undesirable substances precipitate, resulting in clarification of the beer (Nelson and Young, 1986).

Maturation also allows the beer to age and develop esters and related compounds that contribute to flavour and aroma while reducing harshness (Eaton, 2006). To prevent turbidity formation upon later exposure to cold temperatures, chillproofing is often applied during maturation. This process targets unstable proteins responsible for haze formation and involves precipitation or adsorption of these proteins. Proteolytic enzymes are commonly used to reduce the molecular weight of residual proteins (Nummer, 2000). Antioxidants such as ascorbic acid and sulfur dioxide (sulfites) are frequently added during cold storage to prevent oxidative flavour deterioration (Harrison and Nummer, 2000).

After maturation, beer undergoes finishing and carbonation. Carbonation may be achieved naturally through the Krausening method, where actively fermenting yeast is added to the beer, or by injecting purified carbon dioxide recovered from fermentation gas. Krausening typically involves the addition of approximately 15% of actively fermenting wort, allowing residual sugars to be slowly fermented over three to four weeks of cold storage maturation. Excess carbon dioxide produced during this period is vented to achieve the desired final concentration. Alternatively, direct carbon dioxide injection is used to obtain a final dissolved carbon dioxide level of approximately 0.45–0.52%. Carbon dioxide contributes to foam formation and retention and enhances beer stability by displacing dissolved oxygen, which negatively affects beer quality (Lewis and Young, 2001).

Following carbonation, the beer is cooled, clarified, filtered, and packaged in bottles, barrels, or cans.

Pasteurization, Filtration and Packaging

After maturation, beer is prepared for packaging under strictly controlled and sterile conditions, as beer is a short-life beverage and highly susceptible to microbial contamination and oxidation. Packaging is carried out either in kegs or bottles, commonly 330 mL glass bottles. Kegs are available in different capacities, typically holding 30 litres (approximately 50 pints) or 50 litres (approximately 85 pints). Prior to filling, all containers including bottles, kegs, and barrels are thoroughly washed, sterilized, and freed from air to minimize oxidative damage. When beer is bottled, it is counter-pressure filled using a double pre-evacuation system to reduce oxygen pickup. Bottling is often performed by capping on foam, which further limits oxygen ingress and ensures microbiological stability within the bottle. Strict exclusion of air during packaging is essential to maintain beer quality, colour, flavour, and shelf life.

Pasteurization and Filtration

Following ageing, beer may be pasteurized to inactivate residual yeast and spoilage microorganisms, thereby preventing further alcohol production and extending shelf life at room temperature. Pasteurization is generally performed by heating the beer to temperatures ranging from 57–65°C. In some cases, glass containers are pasteurized in advance by slow heating up to 65°C (149°F), which significantly enhances shelf stability. However, pasteurization is not applied in the production of genuine draft beers, also known as "ice beers," which must be kept refrigerated to preserve flavour and slow residual yeast activity. Draft beers are widely regarded as superior in aroma and taste.

Filtration is carried out after maturation to remove both large and small suspended particles, resulting in a transparent and stable beer ready for packaging. Diatomaceous earth filters are commonly used, and bacteriological membrane filters may be employed to remove remaining microorganisms. This filtration step ensures clarity and microbiological safety of the final product.

Packaging, Distribution, and Quality Maintenance

Following cold storage maturation, beer is passed through cooling pipes and filtration systems before being packaged into bottles, cans, or barrels. During packaging, oxygen exposure is strictly avoided to prevent oxidative changes. Glucose oxidase may be used as a stabilizer to remove residual oxygen from the headspace of bottled beer, thereby preserving colour, taste, and flavour and increasing shelf life (Dubey et al., 2017).

Bottled beer undergoes electronic screening to ensure the absence of solid contaminants, haze, or turbidity. Beer quality deteriorates over time due to exposure to sunlight, elevated storage temperatures, agitation, and internal oxidation caused by residual oxygen. Turbidity is one of the most visible forms of deterioration and may arise from insoluble starch, protein–tannin complexes, unstable proteins, resins, or microbial contamination by bacteria and yeast (Bamforth, 2000; Mahalik, 2014).

In addition to conventional processing techniques, emerging and sustainable technologies such as high-pressure processing, ohmic heating, pulsed electric fields, ultrasound, and thermosonication are increasingly being explored in beer processing. The role of these advanced technologies across key stages of the brewing industry has been extensively reviewed (Carvalho et al., 2023).

6. Health benefits of beer

When consumed in moderation, beer has been reported to exert several positive effects on human health. Beer consumption has been associated with enhanced cancer-fighting capabilities, reduced risk of cardiovascular diseases, control of anemia and hypertension, anti-aging properties, and protection against gallstones (Kaplan et al., 2000; Kondo, 2004; Salanţă et al., 2020b).

Studies investigating the health effects of beer consumption present varied viewpoints, as the outcomes depend on multiple variables such as region, lifestyle, socioeconomic status, quality of beer consumed, and the individual's health condition. Excessive beer consumption can lead to alcoholism, which has been reported to reduce life expectancy by approximately 10 years and is considered the third leading cause of early death in the United States. However, moderate beer consumption shows no association with increased mortality or abdominal obesity. In men, moderate beer intake has been linked with a decreased risk of diabetes. The commonly referred condition of "beer belly" is primarily attributed to lack of muscle tone, sedentary lifestyle, and overeating rather than beer consumption itself. Overall, the impact of beer on health is multifactorial and depends largely on consumption patterns and individual health status.

Beer has been shown to provide several health benefits when consumed in moderate amounts (Ore, Mironov and Shootov, 2018). Hops used in beer contain flavonoid compounds such as xanthohumol, which play a significant role in the chemoprevention of cancer, including prostate cancer. Beer consumption has also been associated with a reduced risk of cardiovascular diseases, as it contains vitamin B6, which helps prevent the accumulation of homocysteine. Additionally, moderate beer intake increases bone density, thereby reducing the risk of fractures and osteoporosis.

Moderate beer consumption has been linked to a lower prevalence of type 2 diabetes. Beer is also a good source of vitamin B12 and folic acid, which help prevent anemia. Vitamin B12 further supports normal growth, memory, and concentration. According to biomedical studies, regular beer drinkers tend to have lower blood pressure compared to individuals consuming similar quantities of wine or other spirits.

Beer exhibits anti-aging properties by increasing the potency and impact of vitamin E, a major antioxidant in the body that supports healthy skin and slows the aging process. Regular moderate beer consumption influences cholesterol metabolism by decreasing bile concentration, which reduces the risk of gallstone formation. Beer intake also increases levels of high-density lipoprotein (HDL), or "good cholesterol," by 10–20%, thereby lowering the risk of dementia and coronary diseases.

Beer supports digestive health by stimulating the secretion of gastrin, gastric acid, cholecystokinin, and pancreatic enzymes. The presence of potassium, sodium, and magnesium in beer contributes to a reduced risk of kidney stones, while silicon present in beer is readily absorbed and offers protective effects against osteoporosis. Beer also acts as a stress reliever and facilitates sleep, similar to other alcoholic beverages. Additionally, beer functions as a diuretic, increasing urination and promoting the removal of toxins and waste materials from the body.

7. Conclusion

Beer brewing is a complex biochemical and technological process involving carefully controlled stages such as malting, mashing, wort boiling with hops, fermentation, maturation, and packaging. Each step plays a critical role in determining the quality, stability, flavour, aroma, and safety of the final product. The controlled activity of enzymes and yeast during fermentation and maturation is essential for alcohol production, clarification, and flavour development, while processes such as filtration, pasteurization, and advanced emerging technologies enhance shelf life and microbial stability. When consumed in moderation, beer also exhibits functional and health-promoting properties due to the presence of bioactive compounds derived from hops and malt. Overall, beer represents not only a widely consumed alcoholic beverage but also a product of significant scientific, technological, and nutritional relevance within the food processing industry.

References

Bokulich, N. A., Bamforth, C. W., and Mills, D. A., 2012. A review of molecular methods for microbial community profiling of beer and wine. Journal of American Society Brewing Chemists, 70:150 –162.

Bokulichn, N. A., and Bamforth, C. W., 2013. The Microbiology of Malting and Brewing. Microbiology and Molecular Biology Reviews, 2 (77):157–172.

Campbell, S. L., 2017. The continuous brewing of beer. VI-Food-A-Beer:1-8

Chlup, P. H., Bernard, D., and Stewart, G. G., 2008. Disc stack centrifuge operating parameters and their impact on yeast physiology. Journal of Institute of Brewing, 114:45– 61.

Daenen, L., Saison, D., Sterckx, F., Delvaux, F. R., Verachtert, H., and Derdelinckx, G., 2008. Screening and evaluation of the glucoside hydrolase activity in Saccharomyces and Brettanomyces brewing yeasts. Journal of Applied Microbiology, 104:478 – 488.

Eight degrees brewing, 2018. Brewing Process. Available @ https://www.eightdegrees.ie/brewing process-2/. Accessed on 18/09/2018.

Ferreira, I., Pinho, O., Vieira, E., and Tavarela, J. G., 2010. Brewer's Saccharomyces yeast biomass: characteristics and potential applications. Trends in Food Science and Technology, 21:77– 84.

George Wong, 2003. Role of Yeast in Production of Alcoholic Beverage. Botany135, 1: 30-45.

Keukeleire, D., 2000. Fundamentals of beer and hop chemistry. QUÍMICA NOVA, 23(1):108-112.

Ore, G., Mironov, M., and Shootov, A., 2018. Design and production of maize beer. MOJ Food Processing and Technology, 6(1) :78–87.

Procopio, S., Qian, F., and Becker, T., 2011. Function and regulation of yeast genes involved in higher alcohol and ester metabolism during beverage fermentation.

European Food Research and Technology, 233:721–729.

Sánchez, H. C., 2017. The mathematics of brewing. Available @ http://chalkdustmagazine.com/blog/the mathematics-of-brewing/. Accessed on 18/ 09/ 2018.

Stewart, G. G., 2016. Saccharomyces species in the Production of Beer. Beverages, (2) 34: 1-18.

Verbelen, P. J., Dekoninck, T. M., Saerens, S.M., Van Mulders, S. E., Thev-elein, J. M., and Delvaux, F. R., 2009. Impact of pitching rate on yeast fermentation performance and beer flavour. Applied Microbiology and Biotechnology, 82:155– 167.

Winning-Homebrew, 2018. Controlling Beer Fermentation and Fermentability. Available @ https://www.winning-homebrew.com/beer-fermentation.html. Accessed on 17/09/2018.

* * * * * * * * *