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BEER PRODUCTION BY FERMENTATION PROCESS: A REVIEW

*Goyal Archana[1,†], Shukla Gaurav[1,†], Mishra Shruti[1], Mallik Sarita[1], Singh Anuradha[1] and Dubey Manish Kumar[2]**

Address(es): Dubey Manish Kumar,
[1] Department of Biosciences, School of Basic & Applied Sciences, Galgotias University, Greater Noida 203201, Uttar Pradesh, India.
[2] Department of Biotechnology, University Center for Research & Development (UCRD), Chandigarh University, Mohali 140413, Punjab, India.
†These authors contributed equally

*Corresponding author: mkmkdubey@gmail.com

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Review

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ABSTRACT

Beer is an age-old alcoholic, recreational beverage popular worldwide. It is produced by the process of brewing which involves the enzymatic fermentation of the mixture of water, starch, and hops by yeast in a specific condition. Production of beer from cereal grains involved several steps including grain treatment, malting, mashing, lautering, filtration, fermentation, maturation, finishing, and packaging. The brewing process has a marked effect on the quality, taste, aroma, consistency and alcoholic content. Several types of beers with distinct characteristics can be produced by varying the brewing conditions and yeast flora. Apart from psychoactive affects beer can have several medicinal benefits when consumed in moderation. This review presents a detailed understanding of the several steps for enhancing the brewing process for commercial beer production with desirable quality and flavour. The review also highlights current research progress in the innovative methods and techniques adapted for the cost-effective production of beer, including key advances, potential applications and limitations. Therefore, keeping in view the demands of beer in human daily life, there is an extensive need to commercialize these processes by developing and optimizing novel strategies for cost-effective beer production.

Keywords: Ale, Brewing, Ethanol, Lager beer, Malt, *Saccharomyces cerevisiae*, *Saccharomyces carlsbergenesis*

INTRODUCTION

Beer is considered one of the most popular drinks throughout the world. It may be defined as one of the vital human activities since the dawn of civilization. Beer is primarily prepared from grain and water by using fermentation with the help of yeast **(Campbell, 2017)**. This fermentation process originated thousands of years ago in the Nile Valley **(Meussdoerffer, 2009)**. It has been recorded that the Egyptians were the first to document the brewing process around 5000 BC **(Aroh, 2019)**. The holistic history of 10,000 years of brewing beer is recently provided by **Raihofer *et al*. (2022)** along with the most important discoveries and developments in this field. Due to this huge growth and progress, this industry currently serves as the economic backbone of many European countries. According to a recent report on the contribution made by beer to the European Economy, over 32 million hectoliters of beer were exported from the European Union (EU)-28 countries outside the EU in 2018 **(Salanță *et al*., 2020a)**. This comprises more than 8% of total production. For more development in this sector, it is imperative to increase investment in innovation, particularly to develop new varieties of brews or new beer flavors and expand their production lines. 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 comprehensive review primarily focused on the industrial beer production process by the use of fermentation technology. Herein we discussed the various parameters that needed to be focused on and considered for quality beer production along with their advantages and challenges.

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.

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.

Based on the fermentation process, beer is divided into two types: Top-fermented beer and Bottom-fermented beer **(Figure 1; Table 1; Wunderlich and Back, 2009)**.

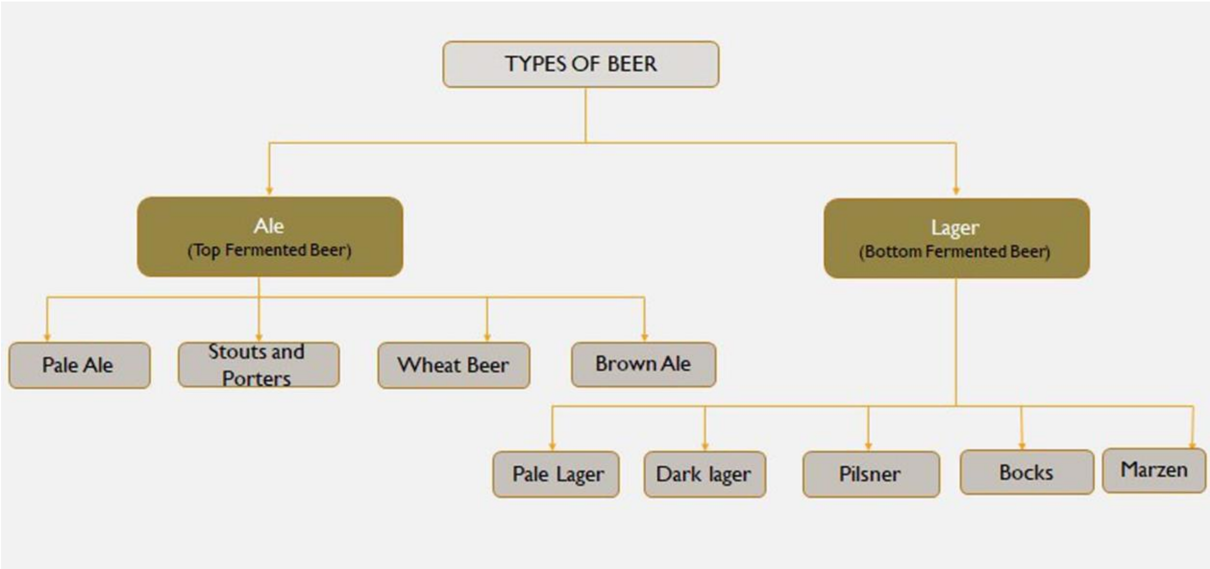

Figure 1 Types of beer

Table 1 Types of beer and their characteristics.

S.No	Types of beer	Colour	Taste	Alcohol Content per vol.	Shelf life	Common Yeast
1.	**ALE**					*S. cerevisiae*
	-Pale ale	Golden to amber	Highly flavourous	3.5-5.5%	Up to 4 months	
	-Porter and Stouts	Black Transparent light straw	Little bitter	5-8%	Up to 6 months	
	-Wheat beer	Copper to brown	Fruity and slightly bitter	4-5.5%	Up to 4 months	
	-Brown ale	Brown	Mild bitter	3.5-4.5%	4-6 months	
2.	**LAGER**					*S. carlsbergenesis*, *S. pastorianus*
	-Pale lager	Light golden	Flavourous	4-5.5%	6-24 months	
	-Dark lager	Dark Brown	Sweet taste	3.5-6%	Up to 6 months	
	-Pilsner	Golden	Bitter	4.5-5.2%	4-6 months	
	-Bocks	Copper-brown	Malty flavour	6-8%	6-9 months	
	-Marzen	Copper or bronze	Malty and sweet flavour	5-6.5%	6-8 months	

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. Due to their warm temperature and the presence of esters, these beers get fermented in 3–5 weeks. 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

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. It was first produced in England.

(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. The taste of this beer is a little bitter or even harsh.

(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.

Bottom fermented beer

Lager beer is the common type of bottom fermented beer that is usually manufactured by ageing in the cold. *S. cerevisiae* 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. 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.

(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.

MEDIUM 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)**. To preclude this problem, the protein, through malt proteolytic activity, first must be degraded totally to amino acids and short-chained peptides before its utilization by the yeast **(O'Connor-Cox and Ingledew, 1989)**. 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."

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*). Other starch sources were also used like maize (corn), rye, oats, rice, sorghum, etc. Conversely, the less used starch sources are millet, cassava root in Africa, potato in Brazil and other starch products in a beer collectively known as grain bill **(Humia *et al.*, 2019; Carvalho *et al*., 2023)**.

Water

Water is the main crucial component for good quality beer because it contains minerals (Calcium Ca^{2+}, Magnesium Mg^{2+}, Sulfate SO_4^{2-}, Carbonic acid CO_3^{2-}, and Chloride Cl). The composition of the water is of extreme importance as it affects flavor and other properties of the beer. 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. 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

Malt is the infusion of grains that have undergone sprouting (malting). It is the 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. Malted grain is the most common form of starch used in the production of beer. 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 this process firstly, the cleaning and grading of barley is performed to remove foreign objects like sand and dust followed by sieving and grading into groups of the barley grains. Small and medium-sized grains are used as animal feed. The next step is called steeping. In this, 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)**.

Malt adjuncts

Some varieties of barley are rich in proteins in comparison to starch. Under these circumstances, the additional starch is added through the addition of rice and corn.

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 CO_2 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)**.

Hops (*Humulus lupulus*)

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.

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.

Mashing

The starch source (often malted barley) is combined with hot water to create the fermentation medium known as wort. In this method, adjuncts are added to water together with milled malt in a ratio of roughly 2/3 malt to 1/3 adjuncts after being boiled to gelatinize their starch. This mixture is subsequently made to undergo mashing or softening of the mixture. The different enzymes in the malt are permitted to work at a variety of temperatures during this process. After the mashing is complete, the wort is removed from the protein debris and undissolved husks, and then it is boiled with hops **(Dewar et al., 1997)**.

The malt's amylolytic and proteolytic activity adheres to a specific temperature range. In general, temperatures of about 60°C allow for the creation of greater molecular weight peptones and peptides, whereas enzymatic activity produces a higher percentage of amino acids and low molecular weight peptides at temperatures of about 50°C. Since yeasts lack proteolytic enzymes, the lower temperature protein breakdown products are crucial for yeast development **(Taylor, 1992; Gomaa, 2018)**.

The ideal temperature range for the activities of malt α-amylase and β-amylases to occur is roughly 57 to 77°C **(Gomaa, 2018)**. The polysaccharides amylose and amylopectin combine to form starch. In contrast to amylopectin, which has a lot of branched chains, amylose is a glucose polymer with straight chains. The β-amylase can only break down the short side chains of linear glucose polymers, excluding the branches of amylopectin, hence enzymatic activity halts at the branching points. It operates best between 57 and 65°C. The α-amylase, on the other hand, cleaves starch at random, producing large-fragment dextrins with or without branching units to make straight chains available for β-amylase activity. The α-amylase has an optimum temperature in the range of 70 to 75°C. Similarly, but more slowly, the dextrins are broken down by the α-amylase to produce smaller fragments **(Olaniran *et al*., 2011)**. However, some of the straight and branched chain fragments of the amylopectin appear to be resistant to breakdown by both enzymes; as a result, these fragments become non-fermentable dextrins **(De Schepper *et al*., 2021)**.

Two mashing techniques exist: infusion mashing and decoction mashing **(Willaert, 2007)**.

(i) Infusion mashing

There are two types of infusion processes: upward and downward. In the upward approach, water and malt are combined at 38 to 50°C. To encourage the action of the proteolytic enzymes, this mash is allowed to rest for about an hour at this temperature. Then, by adding cooked, boiling-hot starchy malt adjuncts, the temperature is increased to 65 to 70°C. For the purpose of saccharification of the starch, the mash is left to stand at this temperature for a short while. The enzymes are subsequently destroyed by raising the temperature to roughly 75°C or slightly higher. The starting temperature of the mash water is raised to around 77°C during the downward mashing process. The temperature rises to about 70°C once the malt is added. The same range of 65 to 70°C is maintained. The temperature is lowered and the processing is performed as before **(Igyor *et al*., 2001)**.

(ii) Decoction mashing

This technique involves mixing the mash at a cooler temperature of about 40°C. The temperature is then gradually increased until it reaches a final temperature of 75°C. About one-third of the initial mash is taken out for this phase, heated, briefly boiled and then added back to the main mash. The heated component raises the mash's overall temperature. The cooked portion's enzymes have been killed, but the starch has dissolved and the cell walls have softened. After that, a fresh amount can be taken, boiled, and added back to the main mash **(Montanari *et al*., 2005)**.
Flavor, foam, and foam stabilization are all provided by the peptones and peptides that the malt produces as a result of its proteolytic activity. While dextrin's non-fermentability results in low-alcohol beer and a few flavour qualities, its colloidal form can also reduce aeration and slow wort filtration **(Moonen *et al*., 1987; Willaert, 2007)**.
Because the optimum pH for certain enzymes might vary, careful pH control during mashing is also crucial. At pH levels between 5 and 5.2, β-amylase and protease are particularly active. The extraction of specific components from malt and its additives, as well as the extraction of tannins and bitter resins from the barley husks, all depend on the pH **(Klimczak and Cioch-Skoneczny, 2023)**. Additionally, coloured extractives are impacted by pH. At higher pH levels, this occurs. Thus, the addition of lactic, sulfuric, or phosphoric acids is used to change the pH levels as needed **(Goode *et al*., 2003)**.

Lautering

Lautering is the process of separating liquid wort from used grain. This procedure separates the wort from the used grains into a separate container known as a "Lauter tun". Spent grains, husks, and other grain debris are left behind as the liquid wort pours from the bottom of the vessel **(Callejo *et al*., 2019)**. Additionally, it aids in the precipitation of solids like proteins. Filter frames, which enable a more finely ground grain, are preferred by some contemporary breweries. The majority of contemporary breweries employ a continuous sparge, gathering both the original wort and the sparge water. It is feasible to gather a second or third wash with the nearly spent grains in separate batches. Every run would result in weaker wort, and subsequently, weaker beer. Second (and third) running is the term for this procedure. Parti-gyle brewing is the practice of brewing with multiple runnings **(Kühbeck *et al*., 2006)**.

Wort boiling or kettle boil

A small number of hops is also added during the wort boiling process, first for bitterness and then for flavour and aroma **(Klimczak and Cioch-Skoneczny, 2023)**. The wort is boiled for a variety of reasons. It makes it easier to extract from hops substances including tannins, essential oils, bitter acids, and resins. Since the aroma is provided by an essential oil, which is volatile, a lot of it actually evaporates during boiling. However, due to the inclusion of hops at the end of the boiling process, some essential oil is preserved in the wort. It also facilitates the extraction of hops components including tannins, essential oils, bitter acids, and resins. The bitter acids humulon and lupulon, which come from hops, have antibacterial qualities and give beer its flavour. Humulon has a strong bitter flavour and stronger antiseptic activity. The tannins included in hop extract aid in the coagulation of extraneous protein and guard the wort during fermentation from contamination by Gram-positive bacteria. As the temperature drops, complexes formed by the reaction of negatively charged tannins and positively charged proteins become less soluble. It facilitates the creation of froth and the distinctively bitter flavour and aroma of beer. Overextraction of the hops, however, may result in additional bitter qualities that are not desired **(Klimczak and Cioch-Skoneczny, 2023)**. The hops and coagulated components are taken out of the wort when the boiling process is complete. "Hot break" refers to the flocculent precipitate layer that develops during the kettle-boiling process. Additionally, leftover hop residues are removed by using a special straining container called hop back in brewing. The mashing process leaves behind some residual and partially hydrolyzed protein that, if not eliminated, could lead to turbidity in the final result. The boiling coagulates this protein. Additionally, boiling concentrates and sterilizes the wort while inactivating the enzymes that were active during mashing and partially caramelizing some sugar. All unstable substances that can precipitate later on in the procedure or the completed product are thus eliminated at this stage **(MacWilliam, 1968; O'Rourke, 2002)**.

Whirlpooling

The liquid wort is stirred into a whirlpool using a spoon or pump. The whirlpooling procedure removes particles that may still be present after boiling. Solid material tends to congregate in the vortex's core during whirlpooling, whereas liquid is pushed outside of the container. "Trub" is the term for solid clumps of particles formed during this process **(Schisler *et al*., 1982)**.

The inoculum

While maintaining aseptic conditions, the filtered wort is aerated and quickly cooled. Before being used as a fermentation medium, the cooled wort may or may not be filtered. The wort is quickly cooled to reduce the risk of contamination, prevent oxidation while it is being transferred to the fermenter, and aid in the precipitation of proteins that could affect the beer's flavour, colour, and clarity **(Boulton, 2020)**. Both bottom and top yeast strains are used in brewing. During fermentation, a top yeast rises to the surface, whereas a bottom yeast sinks to the bottom. The manufacturing of ale (in open tanks) uses top yeasts, which also include distiller's, baker's like *S. cerevisiae*, and wine yeasts. However, bottom yeasts like *S. carlsbergensis* are used in the fermentation of beer and occasionally ale. It is important to choose yeast strains that can both ferment and flocculate at the right moment during the fermentation process. As a result, a distinct industry may choose and cultivate these strains as well as create the inoculum, albeit the brewery itself may also perform these tasks **(Pedersen, 1986; Amory and Rouxhet, 1988)**. Pitching refers to the process of adding yeast to wort. The cells for pitching (inoculating) in brewing are frequently those that have been recovered from a prior fermentation, which sets it apart from most other commercial fermentation. In other words, it's not necessary to prepare fresh inoculum for every fermentation cycle **(Kaneda *et al*., 1992)**. In fact, fresh yeast inoculum is typically only needed when contamination becomes a significant issue or when the energy of the yeast has started to drop. The yeast cells from a prior fermentation are washed (with phosphoric acid, tartaric acid, or ammonium persulfate) by settling, a process that lowers the pH value to about 2.5 and eliminates significant bacterial contamination, if present, before being used as inoculum **(Lodolo *et al*., 2008)**.

Fermentation

Beer fermentation is a naturally unpredictable process that is influenced by the content of the raw materials and the peculiarities of the yeast, among other things. In comparison to open fermentation, closed fermentation is more prevalent since it is simpler to keep unwanted yeasts and bacteria out of the ferment. Additionally, the type of beer and yeast strain used during this process affect temperature maintenance. In actuality, this means that fermentation times for batches of beer of the same quality can differ significantly **(Kaneda *et al*., 1992; Siebert, 2001)**.
A closed fermentation tank with cooling coils is used once the wort has been aerated and chilled to a temperature of 10 to 11°C. Within 24 hours of pitching, foam starts to develop on the medium's surface, first along the tank's wall and then gradually moving across the surface. The rise in carbon dioxide evolution causes the yeast cells to suspend themselves in the media. At this point, the wort is frequently transferred to a second fermentation tank so that weakened and dead yeast cells, proteins that have precipitated, and hop resins that cannot be dissolved can be left behind as a deposit on the bottom of the initial settling or starting tank or trapped in the foam. Additionally aerating the medium also facilitates this process. However, the transfer of the fermentation to a second tank may not be necessary if the boiling and cooled wort has been filtered before the start of the fermentation **(Pilkington *et al*., 1998)**.
The surface foam layer thickens quickly and can reach a depth of up to 12 inches by 40 to 60 hours after pitching. The most rapid yeast cell multiplication happens at this time, and a lot of heat is produced as a result of the intense metabolic activity. The peak temperature for this fermentation is raised by this heat evolution to between 12 and 13°C. Around day five of fermentation, there is no longer enough carbon dioxide evolution to support the thick foam, which causes the foam to start collapsing. Additionally, because the cells are emitting less heat, the medium can be cooled by the cooling coils. During the final stage of fermentation, which lasts seven to nine days, the yeasts "break", or become dormant and flocculate. Some of the surface scum may be taken off at this point to assist the flavour **(Pilkington *et al*., 1998; Solgajová *et al*., 2013)**.

Cold-Storage Maturation

The finished fermentation is transferred to storage tanks or chilled cellars and kept there between 0 and 3°C for a few days to many weeks. Insoluble phosphates, resins, and yeast cells that had coagulated from the beer settled to the bottom during this time **(Nelson and Young, 1986)**. The beer also ages and develops esters, which help it lose its harshness **(Eaton, 2006)**. To avoid turbidity from developing when the finished beer is exposed to cold later, "chill proofing" is frequently used throughout this maturing process. The unstable proteins in beer are mostly to blame for this turbidity. Chillproofing is the process of precipitating or adsorbing unstable leftover proteins. Proteolytic enzymes are used in the chillproofing process to decrease the molecular weight of leftover proteins and protein hydrolysate

products, ensuring their solubility even at low temperatures **(Harrison and Nummer, 2000)**.
In order to avoid oxidative changes in the beer that impact flavor, antioxidants are typically added during cold-storage maturation. Ascorbic acid and sulfur dioxide (sulfites) are frequently utilized to carry out this activity **(Harrison and Nummer, 2000)**.

Finishing or Carbonation

The beer is carbonated either through the "Krausen" procedure, in which yeast that is actively fermenting is introduced to create the purported "natural carbonation," or by the injection of clean carbon dioxide recovered from the generated fermentation gas. The most typical method of adding carbon dioxide results in a final dissolved carbon dioxide level of roughly 0.5 percent in the beer. This carbon dioxide aids in the formation and retention of foam as well as the preservation of the beer by replacing dissolved oxygen, which is harmful to the stability of the beer. About 15% of the active fermentation broth and cells from the early stages of the fermentation are added to beer that is being aged in cold storage as part of the Krausening process. It takes about three to four weeks of cold storage maturation time for these yeast cells to slowly ferment and eliminate leftover sugar. In order to achieve a final level similar to that for carbon dioxide injection, the excess carbon dioxide evolved during this time is vented. After the sugar is utilized, the beer goes through additional cold-storage maturation for a few weeks in order to finish the beer's clarity **(Lewis and Young, 2001)**.

Packaging, distribution and quality maintenance

Following maturation in cold storage, the beer is once more run through cooling pipes and a diatomaceous earth filter before being put into bottles, cans, and barrels. Bacteriological membrane filters can be used to remove microbes from the beer. In order to minimize oxidative changes in the product, air is strictly prohibited during packaging. Moreover, this can be achieved by using glucose oxidase as a strong stabilizer for the removal of oxygen from the top of bottled beer in order to maintain their color, taste, flavor and increase shelf life **(Dubey *et al*., 2017)**.
Additionally, bottled beer is submitted to electronic screening to ensure that no solid contaminants, turbidity, or haze are present. Beer degrades over time, especially in terms of flavour and aesthetic changes. This deterioration is brought on by exposure to sunlight, heated storage, shaking or stirring of the containers, and internal oxidation brought on by lingering oxygen. Turbidity is the most noticeable and easily seen kind of deterioration, and it is brought on by insoluble starch, protein-tannin complexes, unstable proteins, and resins. Turbidity can also be caused by microorganisms like bacteria and yeast **(Bamforth, 2000; Mahalik, 2014)**.
Apart from these processing technologies, nowadays, sustainable and emergent technologies such as high-pressure processing, ohmic heating, pulsed electric fields, ultrasound and thermosonication are being widely used in beer processing. The role of these advanced processing technologies in several key stages of the brewing industry has recently been extensively covered **(Carvalho *et al*., 2023)**.

Health benefits of beer

When consumed in moderation, beer has certain positive effects on one's health. Beer is reported to impart several health benefits such as enhancing cancer-fighting capabilities, Lowering the chance of developing cardiovascular illnesses, controlling anaemia, hypertension, anti-aging attributes and protection against gallstones **(Kaplan et al., 2000; Kondo, 2004; Salanță *et al*., 2020b)**.

Health hazards of beer

More than two 12-ounce glasses of beer a day are generally regarded as unhealthy due to the numerous side effects that can occur, including flushing, confusion, difficulty managing emotions, blackouts, loss of coordination, seizures, irregular heartbeat, and others. Regular, long-term beer use can result in alcohol dependence and have a number of detrimental effects, such as memory loss, heart issues, liver failure, etc **(Bamforth, 2002; Jackowski and Trusek, 2018)**. Recently, **Ciont *et al.* (2022)** highlighted the potential implications of physical, chemical and microbial contaminants in beer for human health. Moreover, this review identified the gaps in current risk reduction or elimination strategies for beer safety during large-scale production.

CONCLUSION

The purpose of this review is to provide in-depth knowledge of production processes or techniques involved in standard beer production by primarily focusing on the approaches employed to improve its characteristics appeal, functionality, nutritional value, shelf-life and to enhance their popularity among consumers. In this sense, several emergent and sustainable technologies regarding beer processing, particularly for high-pressure processing, ohmic heating, pulsed electric fields, ultrasound, thermosonication and glucose electrochemical biosensor can contribute enormously to the development of currently employed brewing methodologies by reducing processing costs and times with better processing efficiency and a more promising environmental friendly approach. Despite this, still more research is needed on these processing technologies to have a wide application of such technologies in continuous beer production. Moreover, lowering the alcoholic content in beer through optimization of fermentation conditions or changes in the mashing regime and by using genetically modified microorganisms can certainly reduce the health hazards of beer. This in the near future can increase the market of non-alcoholic beers. Added to this, more research should be focused on incorporating other alternative raw materials or active ingredients such as Peruvian Andean pseudocereals and starch-rich microalgae in beer brewing as this can increase the farmer's income and brewery profit margin. In this regard, still further research is needed to improve the quality of beer and reduce the total operational cost.

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REFERENCES

Amory, D. E., & Rouxhet, P. G. (1988). Surface properties of *Saccharomyces cerevisiae* and *Saccharomyces carlbergensis*: chemical composition, electrostatic charge and hydrophobicity. *Biochimica et Biophysica Acta (BBA)-Biomembranes*, *938*(1), 61-70. https://doi.org/10.1016/0005-2736(88)90122-8
Aroh, K. (2019). Beer production. Available at SSRN 3458983. http://dx.doi.org/10.2139/ssrn.3458983
Bamforth, C W. (2000). Brewing and brewing research: past, present and future. *Journal of the Science of Food and Agriculture*, *80*(9), 1371-1378. https://doi.org/10.1002/1097-0010(200007)80:9<1371::AID-JSFA654>3.0.CO;2-K
Bamforth, C. W. (2002). Nutritional aspects of beer-a review. *Nutrition Research*, *22*(1-2), 227-237. https://doi.org/10.1002/biof.5520220160
Bokulich, N. A., & Bamforth, C. W. (2013). The microbiology of malting and brewing. *Microbiology and Molecular Biology Reviews*, *77*(2), 157-172. https://doi.org/10.1128/MMBR.00060-12
Boulton, C. A. (2020). Fermentation. In *The Craft Brewing Handbook* (pp. 111-152). Elsevier. https://doi.org/10.1016/B978-0-08-102079-1.00004-7
Cadenas, R., Caballero, I., Nimubona, D., & Blanco, C. A. (2021). Brewing with starchy adjuncts: Its influence on the sensory and nutritional properties of beer. *Foods*, *10*(8), 1726. https://doi.org/10.3390/foods10081726
Callejo, M. J., García Navas, J. J., Alba, R., Escott, C., Loira, I., González, M. C., & Morata, A. (2019). Wort fermentation and beer conditioning with selected non-Saccharomyces yeasts in craft beers. *European Food Research and Technology*, *245*(6), 1229-1238. https://doi.org/10.1007/s00217-019-03244-w
Campbell, S. L. (2017). The continuous brewing of beer. DB Breweries Ltd. https://nzic.org.nz/app/uploads/2017/10/6A.pdf.
Carvalho, G., Leite, A. C., Leal, R., & Pereira, R., 2023. The role of emergent processing technologies in beer production. *Beverages*, *9*(1), p.7. https://doi.org/10.3390/beverages9010007
Čeh, B., Kač, M., Košir, I. J., & Abram, V. (2007). Relationships between xanthohumol and polyphenol content in hop leaves and hop cones with regard to water supply and cultivar. *International Journal of Molecular Sciences*, *8*(9), 989-1000. https://doi.org/10.3390/i8090989
Ciont, C., Epuran, A., Kerezsi, A. D., Coldea, T. E., Mudura, E., Pasqualone, A., Zhao, H., Suharoschi, R., Vriesekoop, F., & Pop, O. L. (2022). Beer safety: New challenges and future trends within craft and large-scale production. *Foods*, *11*(17), 2693. https://doi.org/10.3390/foods11172693
Damjanović, K., & Varga, I. (2021). World beer production and hops use. Research Journal of Agricultural Science, 53(3), 78-84.
De Keukeleire, D. (2000). Fundamentals of beer and hop chemistry. *Quimica Nova*, *23*, 108-112. https://doi.org/10.1590/S0100-40422000000100019
De Schepper, C. F., Michiels, P., Buvé, C., Van Loey, A. M., & Courtin, C. M. (2021). Starch hydrolysis during mashing: A study of the activity and thermal inactivation kinetics of barley malt α-amylase and β-amylase. *Carbohydrate Polymers*, *255*, 117494. https://doi.org/10.1016/j.carbpol.2020.117494
Dewar, J., Taylor, J. R. N., & Berjak, P. (1997). Determination of improved steeping conditions for sorghum malting. *Journal of Cereal Science*, *26*(1), 129-136. https://doi.org/10.1006/jcrs.1996.0101
Dubey, M. K., Zehra, A., Aamir, M., Meena, M., Ahirwal, L., Singh, S., Shukla, S., Upadhyay, R. S., Bueno-Mari, R., & Bajpai, V. K. (2017). Improvement strategies, cost effective production, and potential applications of fungal glucose oxidase (GOD): current updates. *Frontiers in Microbiology*, *8*, 1032. https://doi.org/10.3389/fmicb.2017.01032
Eaton, B. (2006). An overview of brewing. Handbook of Brewing, 92-105. https://doi.org/10.1201/9781420015171.ch3
Eßlinger, H. M. (2009). Fermentation, maturation and storage. Handbook of Brewing: Processes, Technology, Markets, 207-224. https://doi.org/10.1002/9783527623488.ch8
Gerhäuser, C. (2005). Broad spectrum antiinfective potential of xanthohumol from hop (*Humulus lupulus* L.) in comparison with activities of other hop constituents

and xanthohumol metabolites. *Molecular Nutrition & Food Research*, *49*(9), 827-831. https://doi.org/10.1002/mnfr.200500091

Gomaa, A. (2018). Application of enzymes in brewing. Journal of Nutrition and Food Science Forecast, 1(5).

Goode, D. L., Halbert, C., & Arendt, E. K. (2003). Optimization of mashing conditions when mashing with unmalted sorghum and commercial enzymes. *Journal of the American Society of Brewing Chemists*, *61*(2), 69-78. https://doi.org/10.1094/ASBCJ-61-0069

Granato, D., Branco, G. F., Faria, J. de A. F., & Cruz, A. G. (2011). Characterization of Brazilian lager and brown ale beers based on color, phenolic compounds, and antioxidant activity using chemometrics. *Journal of the Science of Food and Agriculture*, *91*(3), 563-571. https://doi.org/10.1002/jsfa.4222

Harrison, M. A., & Nummer, B. (2000). Beer/brewing. Encyclopedia of Microbiology, Four-Volume Set, 412.

Hough, J. S., Briggs, D. E., Stevens, R., & Young, T. W. (1982). Chemical and physical properties of beer. In *Malting and Brewing science* (pp. 776-838). Springer. https://doi.org/10.1007/978-1-4615-1799-3_11 https://doi.org/10.1533/9780857095176.2.133

Humia, B. V., Santos, K. S., Barbosa, A. M., Sawata, M., Mendonça, M. D. C., & Padilha, F. F. (2019). Beer molecules and its sensory and biological properties: A review. *Molecules*, *24*(8), 1568. https://doi.org/10.3390/molecules24081568

Igyor, M. A., Ogbonna, A. C., & Palmer, G. H. (2001). Effect of malting temperature and mashing methods on sorghum wort composition and beer flavour. *Process Biochemistry*, *36*(11), 1039-1044. https://doi.org/10.1016/S0032-9592(00)00267-3

Iorizzo, M., Coppola, F., Letizia, F., Testa, B., & Sorrentino, E. (2021). Role of yeasts in the brewing process: Tradition and innovation. *Processes*, *9*(5), 839. https://doi.org/10.3390/pr9050839

Jackowski, M., & Trusek, A. (2018). Non-alcoholic beer production-an overview. *Polish Journal of Chemical Technology*, 20(4), 32-38. https://doi.org/10.2478/pjct-2018-0051

Kaneda, H., Kano, Y., Sekine, T., Ishii, S., Takahashi, K., & Koshino, S. (1992). Effect of pitching yeast and wort preparation on flavor stability of beer. *Journal of Fermentation and Bioengineering*, *73*(6), 456-460. https://doi.org/10.1016/0922-338X(92)90137-J

Kaplan, N. M., Palmer, B. F., & Denke, M. A. (2000). Nutritional and health benefits of beer. *The American Journal of the Medical Sciences*, *320*(5), 320-326. https://doi.org/10.1097/00000441-200011000-00004

Klimczak, K., & Cioch-Skoneczny, M. (2023). Changes in beer bitterness level during the beer production process. *European Food Research and Technology*, *249*(1), 13-22. https://doi.org/10.1007/s00217-022-04154-0

Kondo, K. (2004). Beer and health: preventive effects of beer components on lifestyle-related diseases. *Biofactors*, 22(1-4), 303-310. https://doi.org/10.1002/biof.5520220160

Kühbeck, F., Back, W., & Krottenthaler, M. (2006). Influence of lauter turbidity on wort composition, fermentation performance and beer quality-a review. *Journal of the Institute of Brewing*, *112*(3), 215-221. https://doi.org/10.1002/j.2050-0416.2006.tb00716.x

Lewis, M. J., & Young, T. W. (2001). Finishing processes. In *Brewing* (pp. 339-350). Springer. https://doi.org/10.1007/978-1-4615-0729-1_19

Linko, M., Haikara, A., Ritala, A., & Penttilä, M. (1998). Recent advances in the malting and brewing industry. *Journal of Biotechnology*, *65*(2-3), 85-98. https://doi.org/10.1016/S0168-1656(98)00135-7

Lodolo, E. J., Kock, J. L. F., Axcell, B. C., & Brooks, M. (2008). The yeast *Saccharomyces cerevisiae*-the main character in beer brewing. *FEMS Yeast Research*, *8*(7), 1018-1036. https://doi.org/10.1111/j.1567-1364.2008.00433.x

MacWilliam, I. C. (1968). Wort composition-A review. *Journal of the Institute of Brewing*, *74*(1), 38-54. https://doi.org/10.1002/j.2050-0416.1968.tb03095.x

Mahalik, N. P. (2014). Advances in packaging methods, processes and systems. *Challenges*, *5*(2), 374-389. https://doi.org/10.3390/challe5020374

Maicas, S. (2020). The role of yeasts in fermentation processes. *Microorganisms*, *8*(8), 1142. https://doi.org/10.3390/microorganisms8081142

Meussdoerffer, F. G. (2009). A comprehensive history of beer brewing. In *Handbook of Brewing: Processes, Technology, Markets*, 1-42. https://doi.org/10.1002/9783527623488.ch1

Montanari, L., Floridi, S., Marconi, O., Tironzelli, M., & Fantozzi, P. (2005). Effect of mashing procedures on brewing. *European Food Research and Technology*, *221*(1), 175-179. https://doi.org/10.1007/s00217-005-1166-8

Moonen, J. H. E., Graveland, A., & Muts, G. C. J. (1987). The molecular structure of gelprotein from barley, its behaviour in wort-filtration and analysis. *Journal of the Institute of Brewing*, *93*(2), 125-130. https://doi.org/10.1002/j.2050-0416.1987.tb04489.x

Nelson, G., & Young, T. W. (1986). Yeast extracellular proteolytic enzymes for chill-proofing beer. *Journal of the Institute of Brewing*, *92*(6), 599-603. https://doi.org/10.1002/j.2050-0416.1986.tb04460.x

Newman, C. W., & Newman, R. K. (2006). A brief history of barley foods. *Cereal Foods World*, *51*(1), 4-7. https://doi.org/10.1094/CFW-51-0004

O'Connor-Cox, E. S. C., & Ingledew, W. M. (1989). Wort nitrogenous sources-Their use by brewing yeasts: A review. *Journal of the American Society of Brewing Chemists*, *47*(4), 102-108. https://doi.org/10.1094/ASBCJ-47-0102

Olaniran, A. O., Maharaj, Y. R., & Pillay, B. (2011). Effects of fermentation temperature on the composition of beer volatile compounds, organoleptic quality and spent yeast density. *Electronic Journal of Biotechnology*, *14*(2), 5. https://doi.org/10.2225/vol14-issue2-fulltext-5

O'Rourke, T. (2002). The function of wort boiling. *Brewer International*, *2*(2), 17-19.

Osman, A. M., Coverdale, S. M., Cole, N., Hamilton, S. E., De Jersey, J., & Inkerman, P. A. (2002). Characterisation and assessment of the role of barley malt endoproteases during malting and mashing. *Journal of the Institute of Brewing*, *108*(1), 62-67. https://doi.org/10.1002/j.2050-0416.2002.tb00125.x

Parker, D. K. (2012). Beer: Production, sensory characteristics and sensory analysis. In *Alcoholic beverages* (pp. 133-158). Elsevier.

Pavsler, A., & Buiatti, S. (2009). Lager beer. In *Beer in health and disease prevention* (pp. 31-43). Elsevier. https://doi.org/10.1016/B978-0-12-373891-2.00003-1

Pedersen, M. B. (1986). DNA sequence polymorphisms in the genus *Saccharomyces* III. Restriction endonuclease fragment patterns of chromosomal regions in brewing and other yeast strains. *Carlsberg Research Communications*, *51*(3), 163-183. https://doi.org/10.1007/BF02907322

Piazzon, A., Forte, M., & Nardini, M. (2010). Characterization of phenolics content and antioxidant activity of different beer types. *Journal of Agricultural and Food Chemistry*, *58*(19), 10677-10683. https://doi.org/10.1021/jf101975q

Pilkington, P. H., Margaritis, A., Mensour, N. A., & Russell, I. (1998). Fundamentals of immobilised yeast cells for continuous beer fermentation: a review. *Journal of the Institute of Brewing*, *104*(1), 19-31. https://doi.org/10.1002/j.2050-0416.1998.tb00970.x

Polak, J., Bartoszek, M., & Stanimirova, I. (2013). A study of the antioxidant properties of beers using electron paramagnetic resonance. *Food Chemistry*, *141*(3), 3042-3049. https://doi.org/10.1016/j.foodchem.2013.05.133

Raihofer, L., Zarnow, M., Gastl, M., & Hutzler, M. (2022). A short history of beer brewing: Alcoholic fermentation and yeast technology over time. *EMBO reports*, *23*(12), p.e56355. https://doi.org/10.15252/embr.202256355

Salanţă, L. C., Coldea, T. E., Ignat, M. V., Pop, C. R., Tofană, M., Mudura, E., Borşa, A., Pasqualone, A., & Zhao, H. (2020a). Non-alcoholic and craft beer production and challenges. *Processes*, *8*(11), 1382. https://doi.org/10.3390/pr8111382

Salanţă, L. C., Coldea, T. E., Ignat, M. V., Pop, C. R., Tofană, M., Mudura, E., Borşa, A., Pasqualone, A., Anjos, O., & Zhao, H. (2020b). Functionality of special beer processes and potential health benefits. *Processes*, *8*(12), 1613. https://doi.org/10.3390/pr8121613

Schisler, D. O., Ruocco, J. J., & Mabee, M. S. (1982). Wort trub content and its effects on fermentation and beer flavor. *Journal of the American Society of Brewing Chemists*, *40*(2), 57-61. https://doi.org/10.1094/ASBCJ-40-0057

Schwarz, P., & Li, Y. (2011). Malting and brewing uses of barley. *Barley: Production, Improvement, and Uses*, 478-521. https://doi.org/10.1002/9780470958636.ch15

Siebert, K. J. (2001). Chemometrics in brewing-A review. *Journal of the American Society of Brewing Chemists*, *59*(4), 147-156. https://doi.org/10.1094/ASBCJ-59-0147

Solgajová, M., Frančáková, H., Dráb, Š., & Tóth, Ž. (2013). Effect of temperature on the process of beer primary fermentation. *Journal of Microbiology, Biotechnology and Food Sciences*, 1791-1799.

Taylor, J. R. N. (1992). Mashing with malted grain sorghum. *Journal of the American Society of Brewing Chemists*, *50*(1), 13-18. https://doi.org/10.1094/ASBCJ-50-0013

Westermann, D. H., & Huige, N. J. (1979). Beer brewing. In *Microbial technology* (pp. 1-37). Elsevier. https://doi.org/10.1016/B978-0-12-551502-3.50006-2

Willaert, R. (2007). The beer brewing process: Wort production and beer. *Handbook of Food Products Manufacturing*, *2*, 443. https://doi.org/10.1002/9780470113554.ch20

Wunderlich, S., & Back, W. (2009). Overview of manufacturing beer: Ingredients, processes, and quality criteria. In *Beer in health and disease prevention* (pp. 3-16). Academic Press. https://doi.org/10.1016/B978-0-12-373891-2.00001-8

Zambrzycka-Szelewa, E., Nalewajko-Sieliwoniuk, E., Zaremba, M., Bajguz, A., & Godlewska-Żyłkiewicz, B. (2020). The mineral profile of Polish beers by fast sequential multielement HR CS FAAS analysis and its correlation with total phenolic content and antioxidant activity by chemometric methods. *Molecules*, *25*(15), 3402. https://doi.org/10.3390/molecules25153402