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Relevant process steps influencing wort and beer composition and its quality: A review

Traditionally beer is made from four raw materials: water, malt, hops and yeast. The first three define the nutrient supply for the latter and compose the wort by the chosen process environment in the brewhouse. Mashing, mash separation and wort clarification define the wort composition and consequently the fermentation performance. This literature review gives an overview of making wort, by taking a closer look at malt and mashing and the dissolution of its components, the mash separation by lautertun and rotary disc filter and its principles, the resulting wort composition which defines the final beer quality by driving the yeast metabolism during fermentation. The review is the basis for a systematic analysis of novel brewhouse worts, based on an integrated, dynamic lautering technology, in comparison to conventional lautertun worts and its effects on the whole brewing process. This comparison will be examined in the next article.

Descriptors: brewing, mash separation, wort composition, beer composition, beer quality, yeast metabolism

1 Introduction

The quality of the beer depends to a large extent on the raw materials used: malt, water and hops. These components determine the quality of the wort. The wort forms the basis for the yeast metabolism that occurs during fermentation – and the yeast has a decisive influence on the finished beer [1]. Only through yeast metabolism, which is composed of carbohydrate, protein, fat and mineral metabolism, does the produced wort ultimately become beer [2]. These conversions serve the yeast to generate energy and to build up new cell substance and consequently cell multiplication [3]. A optimally supplied yeast by the ingredients of the wort, has a positive effect on fermentation [1]. Consequently, there is an “ideal” composition of the wort and thus an optimal supply of the yeast as a guarantee for the best possible fermentation and thus the achievement of the desired beer specifications.

This review gives an overview of the relevant process steps influencing the wort composition which is linked to the resulting beer quality by fermentation. The theoretical principles of mashing, solid-liquid separation, wort composition, fermentation and beer quality, are summarized.

2 Wort production

2.1 Malt and unmalted brewing grains

Barley malt is, along with water, one of the most important raw materials in beer production. Malt and its quality fundamentally determine the taste, colour, foam, stability and aroma of the finished beer [2, 4]. In principle, malt is grain artificially germinated and dried again under precise and controllable conditions for enzyme generation within the grain. The enzymes generated within the grain enable the dissolution of the grain constituents later in the brewing process [5]. For malting and brewing purposes, the two-row spring barley is predominantly used, as it has been systematically bred for high brewing quality [2].

The structure of the barley grain can be divided into outer and inner structure. The outer part of the barley grain consists of the ventral and dorsal husk as well as the base and the apex. The inner part is divided into three main components: embryo, endosperm and grain husk [6]. A barley grain contains 12 – 20 % water and 88 – 80 % dry matter [6]. During malting, the dried and cleaned barley undergoes steeping, germination and kilning [2]. The malt is then stored until delivery.

In order to assess the quality of the barley malt, visual inspections, mechanical analysis and chemical-technical analysis are carried out. The quality characteristics of the MEBAK and the EBC are used as specifications. Here, the characteristics relate primarily to the three important dissolution processes proteolysis, cytolysis and amylolysis. Breeding progress in the last three decades has led to homogeneous and enzyme-strong malts. The limits of the quality characteristics are selected by the brewery itself and are subject to varietal, cultivation, and vintage-related fluctuations [7]. An important parameter is the grade of the malt. A distinction is made between I. grade (2.8 mm), II. grade (2.2 – 2.5 mm) and fines (< 2.2 mm) [6, 2, 8]. Here, at least 85 % of the I. grade should be contained and the fines should not exceed 1.0 % [8].

<https://doi.org/10.23763/BrSc23-15wasmuht>

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Table 1 Chemical composition of light barley malt (extract) [9]

Fraction	Unit	Concentration
Carbohydrates		
Glucose	% dry matter	5.6
Fructose	% dry matter	1.5
Sucrose	% dry matter	2.4 – 3.2
Maltose	% dry matter	34.9 – 37.5
Maltotriose	% dry matter	7.2 – 8.7
Dextrins	% dry matter	22 – 28.3
Protein		
Protein compounds	% dry matter	10.0 – 11.0
Nitrogen compounds	% dry matter	1.60 – 1.76
FAN	mg/100 g	120 – 160
Lipids		
Total fat content	% dry matter	< 2.0
Free fatty acids	mg/100 g	2.2 – 3.0
Minerals		
Potassium	mg/100g	350 – 360
Sodium	mg/100 g	2.5 – 5.1
Magnesium	mg/100 g	70 – 140
Calcium	mg/100 g	72 – 130
Copper	mg/100 g	0.3 – 0.7
Iron	mg/100 g	0.1 – 6.0
Zinc	mg/100 g	0.3 – 5.3
Manganese	mg/100 g	1.4 – 1.5
Polyphenols		
Total polyphenols	mg/100 g	43 – 98
Anthocyanogens	mg/100 g	9 – 25
Vitamins		
Pantothenic acid	µg/100 g	863
Biotin	µg/100 g	17

An extract of the chemical composition of a pale barley malt can be found in table 1. A complete list can be found at *Krüger and Anger* [9].

Instead of malt, it is also possible to use unmalted grain, outside the German Purity Law. Examples include barley, corn, rice, oats, rye or millet [6]. However, pseudocereals such as buckwheat can also be used for brewing beer. In general, the grain content of the total grist load in the conventional lauter tun can be up to 40 %. The enzyme potential of the malt is partly sufficient to break down the additional starch [2]; however, the use of technical enzymes such as proteases, amylases or beta-glucanases is partly required to enable sufficient breakdown into fermentable substrates [4].

2.2 Mashing and the dissolution of the ingredients

In the brewing process, the substances contained in the malt are first dissolved and enzymatically solubilized during mashing. For this purpose, the milled malt is mixed with water and heated under constant stirring, while maintaining certain temperature

levels. During mashing, the enzymatic dissolution process of the malted barley grain is ultimately continued. This is understood to mean the dissolving of the malt ingredients or the breakdown of high-molecular substances into a low-molecular water-soluble form by the malting enzymes [10]. The aim is to obtain as much fermentable extract as possible and to dissolve as little process-inhibiting extract (for example, β -glucans) as possible [11]. The enzymatic processes can be divided into cytolysis, proteolysis and amylolysis.

Various mashing parameters are used to control the dissolution processes during mashing. These include pH, temperature, time or resting, pouring and drawing of boiling mashes. In principle, a distinction is made between two different processes: the infusion process and the decoction process [7]. As a rule, three rests are observed during mashing: a protein rest at 45 °C – 50 °C, a maltose rest at 62 °C – 65 °C, and a saccharification rest at 72 °C. Cytolysis as well as proteolysis are already achieved after malting due to the breeding progress of malting barley varieties. As a result, high short mashing processes or infusion mashing processes with mashing temperatures above 60 °C are practicable [7].

Enzymes are proteins whose catalytic activity accelerates processes or makes them possible in the first place. The activity of the enzyme depends primarily on the specificity and optima of the enzyme. Since enzymes are protein structures, changes in temperature and pH, for example, can lead to denaturation and the cessation of the enzymatic mode of action [12]. The occurring enzymes, their substrate and their pH and temperature optima can be found in table 2 (see page 115).

Depending on the pH value and temperature, the various enzyme optima are achieved. The selected mashing parameters ultimately determine the dissolution of the malt constituents and, as a consequence, the composition of the wort in terms of sugar, protein and mineral content. For example, a low pH during mashing in conjunction with too little water during mashing leads to lower glucose concentrations [13]. In particular, pH and mash temperature have a major influence on mineral solubility [14]. Thus, mash acidification, low mash-in temperatures and a high main pour increase zinc yield [15].

2.2.1 Control of starch degradation

Malt starch, 98% of which is chemically pure starch, is the most important component of the malt kernel. The chains of starch molecules are composed of polysaccharides, amylose and amylopectin [16]. Amylose consists of D-glucose monomers, which are α -1,4-glycosidically linked. Amylopectin consists of α -1,4-glycosidic and linked α -1,6-glycosidic bonds, resulting in a branched structure [16]. The percentage of amylose varies in the literature: 18.2 – 41.3 % according to *MacGregor and Fincher* [17], 27.5 – 29.4 % according to *Morrison et al.* [18] and 17 – 24 % according to *Narziss and Back* [10]. Starch degradation to fermentable extract is divided into gelatinization, liquefaction and saccharification [2]. The α -amylase splits the long chains of amylose and amylopectin and degrades them to low molecular weight dextrins with 6 – 7 glucose residues, while the β -amylase cleaves maltose from the non-reducing ends of starch molecules [10].

Table 2 Enzymes, their optima and products [7]

	Enzyme	Optimum temperature in mash (°C)	Optimum pH in mash	Substrate	Product
Cytolysis	β-glucan solubilase	62 – 65	6.8	β-glucan bound to the matrix	Soluble, high molecular weight β-glucan
	Endo-1,3-β-glucanase	< 60	4.6	Soluble, high molecular weight β-glucan	low molecular weight β-glucan, cellobiose, laminaribiose
	endo-1,4-β-glucanase	40 – 45	4.5 – 4.8	Soluble, high molecular weight β-glucan	low molecular weight β-glucan, cellobiose, laminaribiose
	Exo-β-glucanase	< 40	4.5	cellobiose, laminaribiose	glucose
Proteolysis	Endopeptidase	45 – 50	3.9 – 5.5	proteins	peptides, free amino acids
	Carboxypeptidase	50	4.8 – 5.6	proteins, peptides	free amino acids
	Eminopeptidase	45	7.0 – 7.2	proteins, peptides	free amino acids
	Dipeptidase	45	8.8	dipeptides	free amino acids
Amylolytic	α-amylase	65 – 75	5.6 – 5.8	high and low-molecular α-glucans	melagosaccharide, oligosaccharides
	β-amylase	60 – 65	5.4 – 5.6	α-glucans	maltose
	Maltase	35 – 40	6.0	maltose	glucose
	Limit dextrinase	55 – 60	5.1	limit dextrans	dextrans
Additional enzymes	Lipase	55 – 65	6.8 – 7.0	lipids, lipid hydroperoxides	glycerol + free long chain fatty acids, fatty acid hydroperoxides
	Lipoxygenase (LOX)	45 – 55	6.5 – 7.0	free long-chain fatty acids	fatty acid hydroperoxides
	Polyphenol oxidase	60 – 65	6.5 – 7.0	polyphenols	oxidized polyphenols
	Peroxidase	> 60	6.2	organic and inorganic substrates	free radicals
	Phosphatases	50 – 53	5.0	organically bound phosphate	inorganic phosphate

Starch degradation can usually be monitored by visual iodine assay. Here, a cooled mash sample is mixed with an iodine tincture (0.02 n), which gives a discolouration with starch and high molecular weight dextrans over 11 glucose residues [2]. This colour reaction is based on the bonding of the iodine molecules with the helical structure of the starch molecules [19]. The length of the glucose residues determines which iodine reaction occurs.

If no colouration occurs, the mash is iodine normal and saccharified. The mash can be fed to the next process step, solid-liquid separation. If there is a blue discolouration, the mash is not iodine-normal. This indicates ungelatinized and gelatinized starch and insoluble dextrans with 40 to 100 glucose residues. Furthermore, red-purple blue discolouration is also indicative of erythro-dextrans with 11 to 40 glucose residues. An insufficiently saccharified brew can only be corrected by adding a cold malt extract (= clear, cooled mash supernatant) or by adding mash wort to fermentation [2]. In this case, 0.1 % of the total mash is added to the fermentation as malt extract [20]. The enzymes contained in the malt extract cause post-saccharification, so that no discolouration occurs in a new iodine test and the brew can be described as iodine-normal.

In addition to the optical determination, there is also the possibility of detecting the discolouration photometrically. In this case, the high molecular weight dextrans and starch are precipitated, centrifuged, dissolved, iodine is added and then measured in a photometer at an absorbance of 578 nm [21]. The limit value of the measured absorbance (ΔE) in a wort ready for preparation is 0.45 [22].

Elevated iodine levels are reported to result in low extract yield, microbiological instability, turbidity (starch haze), precipitation, filtration difficulties, reduced final fermentation degrees, and loss of flavour [2, 23]. However, the tolerance of the limit value varies in the literature also taking the methods with and without buffer into account. According to MEBAK it is 0.45 [22], according to Narziss it is 0.25 [24] while *Annemüller* and *Anger* consider 0.2 [25] to be good. Regarding the predicted filtration problems, *Kupetz et al.* [26], showed that the iodine value does not provide any information about the filterability. In this context, *Zeuschner* and *Pahl* [23] draw attention to the fact that the measured iodine values do not always lead to the predicted consequences and that the iodine value should be seen as a sum parameter for α-glucans due to the wavelength.

2.2.2 Mass transfer

During mashing, the enzymatically dissolved malt constituents are transferred to the liquid phase, the wort. In this process, the malt is opposed by the solvent water. This is known as mass transfer. This is understood to mean the transport of several components of a mixture within a phase or across phase interfaces [27]. The mass transfer, due to Brownian molecular motion, from one phase to another phase through a phase boundary is referred to as mass transfer [28, 27]. The existing concentration gradient determines the speed of the transport. Simplified, this is fundamentally diffusion in solids. Mass transfer due to diffusion is defined by Fick's law [29]. Here, the diffusion coefficient depends on the concentration gradient, the diffusing substance, the substance at rest, the prevailing

pressure and the temperature [27].

Mass transport can be described using the film theory of Lewis and Whitman [30, 27]. The malt is surrounded by a fluid film and the dissolved substances diffuse into the liquid. In addition, mass transfer occurs by convection. This is defined as mass transfer between a moving fluid and a phase boundary and can be forced by external flow, such as stirring or pumping [27]. The solutes in the high concentration range (= malt) diffuse into the low concentration range (= water) until a concentration equilibrium is reached [27, 29]. The dissolved substances are then dispersed in the liquid phase (= wort).

2.3 Principles of solid-liquid separation in the brewing process

The substances of the malt now dissolved in the mash are obtained in the form of wort during the solid-liquid separation of the mash, the lautering process. During this process, the insoluble components of the mash are separated from the wort [31]. This is based on the various mechanisms of action of filtration and extraction.

2.3.1 Filtration

Filtration is a mechanical separation process that separates a suspension consisting of a discontinuous phase and a continuous phase into liquid and solid components [29]. In this process, the solids of the fed suspension are retained with the help of a filter medium (sieve, filter cloth, filter paper) and are deposited on the filter medium. Meanwhile, the liquid flows through the filter medium and the solid layer formed [32]. The filtered liquid, also called filtrate, leaves the filter media clarified. The pressure difference between the suspension and filtrate sides applied during filtration represents the driving force [29].

Basically, a distinction is made between static and dynamic filtration. Static filtration is divided into sieve filtration, where the solid particles are retained on the filter medium, and depth filtration, where the particles are retained in the filter medium [33]. The processes involved are shown schematically in figure 1. The filtration types shown are referred to as "dead-end filtration", since the filter medium blocks after a certain time and filtration must be stopped [34].

During sieve filtration, all solid particles larger than the pore size of the filter media are retained on the filter media. Consequently, the separation effect is based on the pore size of the filter media

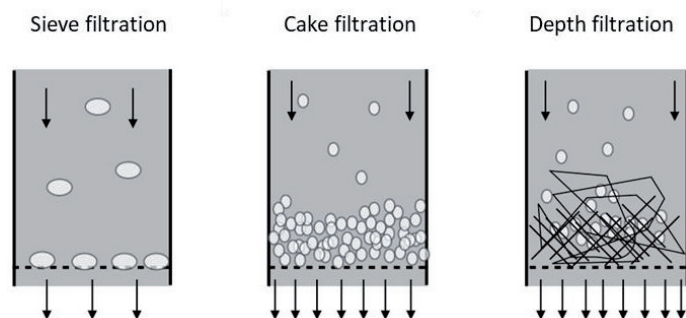


Fig. 1 Model concepts of static filtration [33]

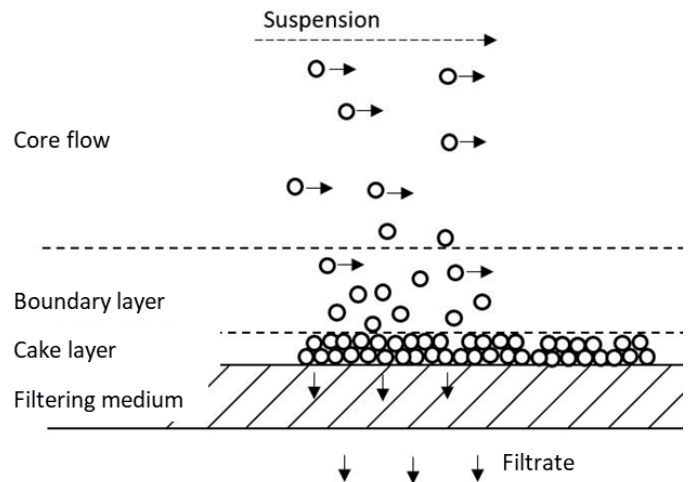


Fig. 2 Schematic illustration of dynamic filtration [37]

[32]. As the particles remain on the filter media, the pores become increasingly clogged. At high solids contents, sieve filtration can change to cake filtration [32].

In cake filtration, solids of a suspension are retained on the surface of the filter media. These form a filter cake without themselves penetrating the layer [32]. Initially, as in sieve filtration, the separation effect is based only on the pore size of the filter medium. The coarse particles of a suspension are retained and deposited on it. With increasing filtration time, these form a growing filter cake, which takes over the actual separation effect [32, 35]. Thus, a depth effect is usually also achieved with cake filtration [29].

Depth filtration here is based on adhesive forces that arise and can retain the particles fed into a suspension. The separation effect takes place in the filter medium, which consists of larger grains or fibres. The solids of the suspension are transported by inertial and electrostatic forces to the inner surface of the filter medium, where they adhere due to intermolecular forces. The particles retained in this process are much smaller than the pores of the filter media because filtration is based on physicochemical mechanisms [36, 32, 34].

While the direction of flow of suspension and filtrate is identical in the types of filtration just described, suspension and filtrate flow orthogonally to each other in dynamic filtration. This type of filtration is called cross-flow filtration. The build-up of a filter cake is counteracted. The filtration effect is based on the filter medium [32, 37]. Figure 2 shows the schematic diagram of a dynamic filtration.

The filter medium is overflowed with the suspension to be separated. The resulting shear stress prevents particle deposition and limits the filter cake height. A very low layer thickness, the cake layer, is built up. Due to the occurring wall shear stress, the particles deposited on the filter media are transported back into the core flow [32, 37].

2.3.2 Extraction

Solid-liquid extraction allows the extraction of soluble components from a solid using a liquid extractant [38]. The extractant, the

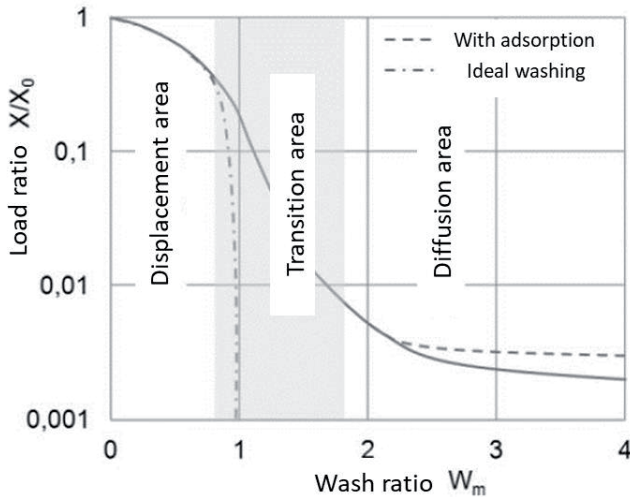


Fig. 3 Schematic washing curve [42]

carrier and the soluble components form the main components of the process. During the extraction, the solid is flown through by the extraction agent. In this process, the soluble substances of the solid diffuse into the extractant [39]. This process can be supported by comminution of the extraction material. If water is used as the extraction agent, solid-liquid extraction is also referred to as lixiviation [39].

In addition to filtration, extraction also plays an essential role in the brewing process in order to dissolve out the remaining extract components in the spent grains [40]. The solid-liquid extraction is based on the difference in extract between the spent grains and the sparging liquor water [2]. In conventional solid-liquid separation processes in breweries, the spent grains, the carrier, are present as a fixed bed and are passed through by the preweaning water, the extracting agent. The remaining sugar is dissolved out as a soluble component.

2.3.3 Theoretical consideration

The theoretical consideration of the lautering process is composed of various steps. On the one hand, mechanical filtration takes place in combination with sedimentation, and on the other hand, the resulting spent grains layer is later washed out by means of extraction and liquid displacement.

The theoretical considerations of filtration are based on Poiseuille's law [32]. This describes laminar flows through capillaries with a circular cross-section [29]. In addition to this, the basic equation of filtration according to Darcy must be taken into account [33].

This describes the laminar flow through a porous layer. Here, the volume flow is proportional to the pressure difference through the filter layer with thickness. The layer must be incompressible [29].

The flow rate therefore increases the higher the pressure difference and the lower the viscosity. The relationship between permeability, porosity and specific surface area is represented in the Carman-Kozeny equation [41].

The theoretical ideal of washout is characterized by liquid displacement without back-mixing. The mass ratio of wort and spent grains present in the spent grains cake (= X_0) and the mass ratio of the wash liquid (sparging liquor) and the liquid present in the pore space (wort) (= X) are related as shown in equation 1 (Calculation of the loading ratio) [42].

$$\frac{X}{X_0} = 1 - W_m \tag{Eq. 1}$$

mit X/X_0 = Loading ratio

W_m = Wash ratio

If the flow-through wash is ideal, $W = 1$. This ideal wash is shown, next to the real wash, in figure 3.

However, the washing that occurs in reality (see solid line in Fig. 3) is determined by the dispersion and diffusion taking place in parallel. The washing curve (= solid line) is significantly lengthened, since instead of a sharp transition between the washing liquid and the mother liquid, a mixing zone is created. The typical transition range of filter cake washing is at a wash ratio of 0.8 – 1.5. At the end of the washing process, the wash curve flattens out, due to adsorptive binding of the particles. This means the composition of the filtrate and the washing liquid equalize [42].

If solid/liquid separation steps and a resuspension of the wet solid with a pure washing liquid are performed, this is called dilution washing. A schematic illustration can be found in figure 4.

Here, the concentration of the wort changes only in the dilution step, while the concentration remains the same in the separation step. The concentration of the filtrate is given as a mass- or volume-related variable and can be calculated taking the wash ratio and saturation of the single washing steps into account [42]. Few parameters determine the process of dilution washing. The greater the dilution and thus also the washing ratio, the fewer steps of resuspension or remixing are required. The optimum number of repetitions lies in the economic consideration [42].

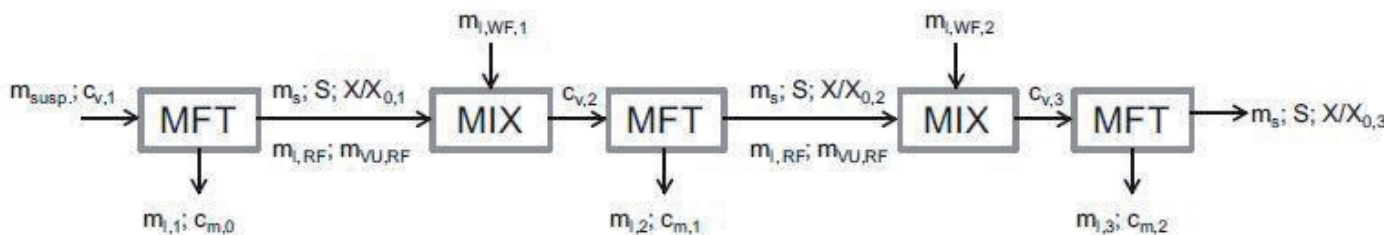


Fig. 4 Schematic sequence of a dilution wash with two mixing stages (MIX) and three dehumidification stages (MFT); m = mass, c = concentration, v = volume, S = saturation, X/X = load ratio, VU = impurity, RF = residual moisture, susp. = suspension, l = liquid, WF = washing liquid [42]

2.4 Mash separation

The solid-liquid separation, which has just been theoretically described, is an important process step in beer brewing. Solid-liquid separation is traditionally carried out in breweries by means of lauter tuns or mash filters [2]. In addition to these methods, other separation options have been developed, such as the strainmaster or the use of a rotary drum vacuum filter, hydrocyclone, or decanter, but these have not become widely established [10, 43, 44, 45, 40]. The rotary disc filter represents another novel option for mash filtration [46]. In the present paper, the mechanisms of action of the lauter tun and the rotary disc filter are examined in more detail; the mash filter is not considered.

2.4.1 Lautertun

The lauter tun represents the original and widely used option for separating the mash. Separation takes place through the spent grains and is based on a combination of sieve, cake and depth filtration [10, 2, 47].

The regular lauter tun, besides special shapes, is essentially a round insulated stainless steel vessel. This is equipped with a perforated bottom, the false bottom, several taps, a raking unit and a drive motor [29]. The false bottom, which acts as a support layer for the spent grains, is designed either as a slotted screen or as a wedge wire screen and has a distance of 10 – 20 mm from the bottom of the vessel [2]. One tap hole with a drainage cone is provided per m² of lauter tun bottom to enable uniform lixiviation of the spent grains [2]. The raking unit serves to loosen up the spent grains cake and has a significant influence on the lautering time and the clarity of the wort. The raking unit and the raking height are controlled depending on the volume flow, the pressure difference and the turbidity value [2].

The capacity of the lauter tun is determined by the total mash volume or by the bulk density [20]. The footprint is designed according to the grist type (dry or wet grist) and the resulting spent grains height. These parameters and the number of brews determine the specific false bottom load. The specific false bottom load is an important parameter of the lauter tun and describes the malt mass that rests on one square meter of lauter tun surface [10]. The false bottom load depends on the grist type and false bottom.

In order to ensure the function of the lauter tun, the mash must be saccharified. Not saccharified worts can only be lautered at a slower rate and exhibit reduced clarification [24]. In addition, the grist must adhere to a certain composition. Protection of the husks plays a special role, as these form the first natural filter layer [10]. The typical composition of a dry lauter tun grist is usually produced with a roller mill and is composed of husks (18 – 25 %), coarse grist (< 10 %), fine grist I (35 %), fine grist II (21 %), flour (7 %),



Fig. 5 Model illustration of the rotary disk filter [53]

and powdered flour (< 15 %) [48].

Solid-liquid separation using the lauter tun requires approximately 120 minutes and allows 12 – 14 brews per day [2, 49].

The solid undissolved components of the mash, especially the husks, settle on the false bottom and form a filter cake after turbidity pumping. With increasing duration, the finer particles are deposited on it and cause the filter layer to grow and become more finely porous; zone sedimentation occurs. An upper and lower dough layer with different permeabilities is formed. Consequently, as mentioned at the outset, wort recovery using the lauter tun is based on the various interacting mechanisms of screen, cake and depth filtration in the spent grains [10, 47]. Washing out of the spent grains during sparging is based on solid-liquid extraction with warm brewing water [2]. The extract difference is the driving gradient between spent grains and sparging water and enables further leaching of the spent grains [2].

Modern lauter tun enable the production of clear wort with solids content below 35 – 50 mg/l [50, 51]. The ongoing optimizations for the production of clear worts are industry-driven as a competitive advantage and demonstrably changed the wort composition. It has been demonstrated that high wort turbidity is associated with increased lipid and zinc contents [20, 52, 47]. Consequently, with decreased wort turbidity, the content of these ingredients decreases. This means that ingredients are retained by the depth filtration present in the lauter tun [47, 20].

2.4.2 Rotary disc filter

The use of a rotary disc filter for mash filtration represents a novel separation technology in this field. The main components of the new lautering unit are four cascaded rotary disc filters. Figure 5 shows the basic design of the new lautering unit with a capacity of 80 hl/h.

The lauter system consists of four identical modules, which are interconnected by three transitions. The sparging liquor water is fed into these transitions via spray nozzles. In addition, so-called weirs are installed in the transition zones, which create additional

turbulence by disturbing the flow. This intensifies the contact between the residual mash and the precoat water and enables extraction.

Each module contains a wheel pair. This consists of two sintered stainless steel sieve discs with a pore size of 70 μm . The sieve discs are arranged parallel to each other on a central drive shaft. During mash filtration, the wheel pairs are in rotating motion and enable separation. The wall shear stress created by the rotational speed prevents the build-up of a filter layer. It is a dynamic filtration.

For solid-liquid separation of the mash, it is fed into the first module from below. The mash now flows between the rotating pair of wheels. The permeate, the wort, flows off through the sieves under hydrostatic pressure. The rotational movement supports self-cleaning and thus prevents blocking of the sieves. Consequently, the passage surface of the sieves remains free throughout the entire filtration process. This also prevents the build-up of a filter cake. No pressure loss occurs during the process. The retentate remaining through the sieves, consisting of residual mash and spent grains, is conveyed by the rotary motion to the transition point. Here, the mixture passes by gravity into the next module. Meanwhile, the sparging liquor is continuously impinged in the transition to obtain remaining extract. The mixture diluted in the transitions enters the next module and is filtered again. This process is repeated until the wort exits the last module, and thus the wort concentration decreases over the entire process.

The filtration principle is based on dynamic sieve filtration without the build-up of differential pressure. Mash separation by means of the rotary disc filter enables a continuous wort flow and a continuous spent grains discharge. The mashing time thus ultimately corresponds to the lautering time. This type of continuous filtration shortens the process of mash separation and the residence time of the particles in the separation process. This reduces the leaching of undesirable substances from the spent grains, such as tannins and silicates. Easily soluble substances, such as extract and minerals, on the other hand, pass unhindered into the liquid/wort.

Since the process is mainly based on sieve filtration, a natural supporting layer of husks is no longer required as a filter medium. Consequently, the malt is milled finer, as the husks do not have to be retained. In addition, the lautering process allows a mashing temperature of 72 $^{\circ}\text{C}$, since a further temperature increase to reduce viscosity for lautering is not necessary due to the sieves.

The novel lautering produces worts that differ from conventional and traditionally produced worts. Wort turbidity, measured in solids, reaches between 0.9 g/l in clear phases to 18 g/l in turbid phases, up to 48 times higher than in a lauter tun wort [54]. In previous studies, individual substance groups could be narrowed down [55, 56]. The concentrations of fatty acids and minerals are increased, while the concentrations of introduced tannins are reduced. The altered wort composition is due to the filtration principle of the rotating disk filter. On the one hand, the contact time within the process is greatly reduced, so that substances such as tannins are not washed out. On the other hand, due to the lack of depth filtration, substances such as long-chain fatty acids are transferred into the wort down [55, 56, 53, 57, 46].

2.4.3 Trub separation

The separated wort is then boiled together with hops. The break of the cast-out wort formed by boiling is called hot trub and is defined as a solid insoluble in heat [2, 24]. The trub consists of a mixture of insoluble proteins, carbohydrates, lipids, tannins, minerals and hop constituents [47]. In this, 80 % water is contained. The dry matter is composed of 50 – 60 % proteins, 20 – 30 % organic substances from malt and hops such as polyphenols, fatty acids and carbohydrates, 15 - 20 % bitter substances and 2 – 3 % minerals, depending on the brewing water [58, 24]. The trub occurs in larger particles between 30 – 80 μm and falls to about 40 – 80 g/hl dry matter (at 12 wt.% wort) [2, 58, 24]. Due to the size and density difference from the wort, these particles can be separated by sedimentation [36, 24, 2]. Removal of the trub is recommended on the one hand because it can hinder further beer production. Removal of the hot trub is said to contribute to a cleaner yeast, improved foam and flavour stability, and better clarification of the finished beer [2, 24, 59, 29]. On the other hand, extremely clear wort was also shown to be detrimental to fermentation. Too sharp trub separation leads to a lack of nutrient supply to the yeast. Substances contained in the wort, such as long-chain fatty acids or zinc, can increase fermentation performance, in terms of higher cell concentration of yeast, allow low pH values and faster extract degradation, and reduce CO_2 inhibition [2, 24, 52, 60].

Options for trub separation include whirlpools, centrifuges, filtration systems, or settling in a cooling vessel or settling vat [10, 29].

2.5 Wort composition

Wort dissolved solids consist of up to 90 – 92 % carbohydrates and 4 – 5 % nitrogen compounds [61]. The remaining ingredients are composed of minerals, lipids and vitamins [20]. The concentration of the wort is usually measured in degrees Plato ($^{\circ}\text{P}$) and referred to as original wort. It should be noted that all soluble, non-volatile substances are included in the measurement and are summarized as extract and original wort, respectively [22].

Table 3 Carbohydrates and their concentration in a beer wort [62, 22, 9]

	Unit	MacWilliam [62]	MEBAK [22]	Krüger/Anger [9]
Wort type	–	Lager	Pale	Pale
concentration	$^{\circ}\text{P}$	12.0	12.0	12.0
Fructose	g/l	3.9	1.9	1.9
Glucose	g/l	14.7	8.5	8.5
Saccharose	g/l	4.6	3 – 5	3 – 5
Maltose	g/l	57.8	54 – 64	53.6 - 63.8
Maltotriose	g/l	14.6	11 – 13	3 – 15.6
Maltotetraose	g/l	–	–	3.5
Dextrins	g/l	–	–	1.44
Fermentable sugars (total)	g/l	95.6	88.8	–
Sugar (total)	g/l	–	108.0	109.2
Degree of fermentation	%	–	74	–

The sugars contained in the wort are composed of maltose, glucose, fructose, sucrose, maltotriose, maltotetraose and higher molecular weight dextrans. Typical sugar compositions of various worts can be found in table 3.

Maltose accounts for the majority of the fermentable sugars (60 – 65 %). The remaining proportion is made up of glucose, fructose, sucrose and maltotriose. Approximately 25 % of the carbohydrates contained in the wort, such as maltotetraose and dextrans, cannot be utilized by brewer's yeast and are thus considered unfermentable extract [63]. The composition of the remaining extract is excerpted in table 4.

The wort contains up to 700 – 1000 mg/l nitrogen compounds [64]. These are composed of 20 % protein, 22 % polypeptides and 58 % peptides and free amino nitrogen [65]. In particular, free amino nitrogen is crucial for an adequate supply of yeast during fermentation and should be present in the wort at a minimum of 150 – 230 mg/l [66, 7]. The amino nitrogen content influences the formation of some metabolites, such as vicinal diketones, higher alcohols, esters, carbonyls, and sulphur compounds, and consequently the taste of the finished beer [67].

The lipid content of the wort is determined by the lautering process and trub precipitation [20, 68, 69]. In this context, the wort turbidity must be taken into account [70]. Thus, a positive correlation between lauter turbidity and the content of lipid substances has

Table 4 Chemical composition of a barley malt wort (extract) [9, 63]

Fraction	Unit	Concentration
Protein		
Protein compounds	% dry matter	0.5 – 0.7
Nitrogen compounds	ppm	700 – 1000
FAN	ppm	150 – 200
Lipids		
Total fat content	ppm	4.5 – 5.6
Free fatty acids	ppm	1.4 – 2.5
Minerals		
Potassium	ppm	550
Sodium	ppm	30
Magnesium	ppm	100
Calcium	ppm	35
Copper	ppm	0.02 – 0.4
Iron	ppm	0.1 – 0.27
Zinc	ppm	0.01 – 1.08
Manganese	ppm	0.12 – 0.14
Polyphenols		
Total polyphenols	ppm	46 – 418
Anthocyanogens	ppm	12 – 175
Vitamins		
Pantothenic acid	ppb	150 – 250
Biotin	ppb	5 – 18
Protein	ppb	40000 – 45000

been demonstrated [50, 71, 72, 20, 52, 73]. But an excessive lipid content may contribute to increased aging of the beer [73]. On the other hand, too sharp trub separation leads to a lack of lipid supply to the yeast [24].

Vitamins and minerals also pass into the wort. The concentration of minerals depends largely on the malt and brewing water and is therefore subject to fluctuations [74]. It also depends on the wort turbidity. For example, the zinc content increases with increasing wort turbidity [51]. The mineral content must be taken into account, especially with regard to fermentation, since these act as cofactors of the enzymes [75]. In this context, the magnesium-to-calcium ratio should also be mentioned. Not only the concentration of minerals per se, but their ratio to each other is supposed to have a decisive influence on fermentation intensity and yeast condition. A ratio greater than two is recommended in the literature [76, 77]. Bromberg et al. [78] on the other hand, showed in their experiments that the ratio has no further influence on fermentation.

Polyphenols are released during mashing, lautering and boiling. The resulting polyphenol content depends on the temperature and duration of the processes [20]. If the polyphenols undergo oxidation, this leads to a coloration of the wort. In addition, polyphenols can later cause beer turbidity in combination with proteins in the finished beer. High-molecular polyphenols, which occur in the finished beer, reduce the stability of the beer foam through oxidation. Low molecular weight polyphenols are considered to be foam positive [2, 79]. It has been demonstrated that anthocyanogens influence yeast metabolism and, as a result, higher diacetyl contents occur [80].

3 Fermentation and beer

As shown above, the wort composition depends on the malt and selected mashing parameters and the solid-liquid separation. The constituents of the wort correspond to the washed-out and converted constituents of the malt, and undergo further conversion during fermentation by yeast metabolism. The fermentation is depending on the nutrient of the yeast by the wort. Furthermore the yeast and its physiological state influences the fermentation and the finished beer as well.

3.1 Yeast metabolism and fermentation by-products

Brewer's yeast of the genus *Saccharomyces* is the most important microorganism in the brewing process [1]. A distinction is made between top-fermenting (*cerevisiae*) and bottom-fermenting (*pastorianus*) yeast [81, 82]. Within the brewing process, yeast metabolism is subject to changing aerobic and anaerobic conditions as well as the constituents of the wort. The energy and building metabolism that occurs during fermentation includes carbohydrate, protein, mineral, and fat metabolism [1, 24, 63].

Carbohydrate metabolism

In brewing, the focus is on the breakdown of fermentable carbohydrates to CO₂ and ethanol. The initial product of this process is glucose. Monosaccharides, such as glucose, are the most efficient carbon sources for yeast metabolism and are initially taken up via

diffusion and facilitated diffusion. Only after the glucose concentration decreases, the higher molecular weight sugars such as di- and trisaccharides are metabolized. The uptake of maltotriose proceeds with energy expenditure. If the nutrient requirement of a vital yeast and the multiplication rate is increased, the more energy-consuming sugars are also taken up [83, 84, 85]. The assimilable organic carbon sources are taken up via active transport systems (permeases), converted to glucose in the cell, and degraded to pyruvate in glycolysis. This is introduced into the mitochondria during respiration in the citrate cycle; during fermentation, pyruvate is degraded in the cytoplasm [86, 2]. Aerobic energy gain from oxidative phosphorylation is 38 ATP, whereas 2 ATP per glucose molecule is gained under anaerobic conditions [1, 24, 87]. The metabolic conversion of sugars at anaerobic conditions by yeast additionally leads to the formation of ethanol and carbon dioxide [88]. The metabolic process stimulated by yeast in the brewery is called alcoholic fermentation and describes the biochemical degradation of carbohydrates in the absence of air [2, 24]. *Balling* [89] shows in his theory of attenuation that fermentation is subject to computational relationships: from 2.0665 g of extract, an average of 1 g of alcohol, 0.9565 g of carbon dioxide, and 0.11 g of yeast are produced [21]. Fermentation metabolism can also take place in aerobic conditions as soon as the sugar concentration exceeds 0.1 g/l. The so-called Crabtree effect describes catabolite repression by glucose [1]. This can also be transferred to the other carbohydrates of the wort and thus forms the basis of the fermentative conversion of beer wort, since the conditions of the Crabtree effect are always fulfilled [1]. The anabolic metabolism includes the formation of the reserve substances such as trehalose and glycogen [63].

Protein metabolism

Besides carbon, nitrogen is considered the main nutrient of brewer's yeast. The amino acid content of the wort is important for the biosynthesis of proteins, the transport and storage of all nutrients, and all metabolic processes taking place [24]. Adequate nitrogen supply to yeast is critical for the assembly and incorporation of transport proteins into cell membranes, the provision of DNA building blocks, and the synthesis of enzymes [74]. Consequently, nitrogen supply is a limiting factor in fermentation.

Beer wort contains amino acids, peptides, proteins, purines, and pyrimidines. The complexity of the compounds has a great influence on yeast metabolism [1, 74, 90]. Yeast is able to use amino acids and simple peptides of the wort as a nitrogen source, but cannot directly assemble them into cellular proteins. For this purpose, the amino acids necessary for protein synthesis are synthesized from simple compounds of the intermediary metabolism of respiration and fermentation. In this process, the amino group of the wort amino acids is transaminated onto the formed keto acid of the yeast. Fermentation by-products are formed from the resulting deaminated wort amino acids during fermentation [1].

The minimum content of available free amino nitrogen in a 100 % malt wort is between 150 – 230 mg/l [66, 7, 1]. Should a deficiency of FAN occur, this is reflected in lower yeast propagation and fermentation intensity [74]. Also, in the case of FAN undersupply, the concentration of α -keto acids decreases, thereby leading to an altered composition of fermentation by-products. For example,

underbalanced FAN results in increased acetoxyacid contents. This causes longer maturation times. The FAN content also influences the formation and reduction of 2-acetolactate. Ideally, the FAN content decreases to 20 – 40 mg/l by the time the beer is finally fermented. Higher final contents indicate an undersupply of the yeast or technological errors [1, 74, 63].

Lipid metabolism

The yeast's own lipid metabolism has a decisive influence on yeast growth and condition. Lipids are crucial for the structure of the cell membrane in terms of membrane fluidity and permeability as well as the activation of membrane-bound enzymes. This enables rapid uptake of fermentable sugars, amino acids, essential wort ingredients and cell proliferation [91]. A deficiency of long-chain unsaturated fatty acids leads to a deterioration in the cell membrane's ability to absorb them and, as a consequence, to a possible standstill in the uptake of amino acids [2]. Consequently, the yeast cell must be supplied with sufficient fatty acids, phospholipids and sterols.

The cell membrane is composed of yeast lipids and protein [92, 74]. Here, lipids make up 80 % of the dry matter of the cell wall and are integrated into the cell wall as long-chain and unsaturated fatty acids [24, 74]. These facilitate phosphate transport, uptake of nutrients such as amino nitrogen, and activate ATP enzymes [74]. In addition, the incorporation of long-chain fatty acids in the membranes increases ethanol tolerance [3, 93, 94].

Since yeast growth requires an increased substance concentration of lipids, which cannot be covered by the wort, yeast forms lipids via fatty acid synthesis [24]. This takes place in the initial stage of yeast propagation in conjunction with oxygen [63]. Ergosterols, an important structural lipid, and unsaturated fatty acids can only be formed when oxygen is available [95]. In order to ensure oxygen supply in breweries, the wort is specifically aerated [1]. Acetyl-CoA is one of the most important substrates for fatty acid synthesis. This occupies a key position in several metabolic reactions, forms the hub of the synthesis of saturated and unsaturated fatty acids, and is linked to the formation of acetic acid and fatty acid esters. The condensation of acetyl-CoA and malonyl-CoA produces saturated fatty acids. With the participation of molecular oxygen, to form double bonds, and NADPH₂, unsaturated fatty acids of the same chain length are formed from these saturated fatty acids [24, 74, 96].

Mineral metabolism and growth substances

Although mineral and growth substances are present in low concentrations in worts, they play a crucial role in the physiological state of yeast and cell structure [1]. Sulphur, phosphates, zinc, calcium, magnesium, iron, copper, and potassium ions, as well as vitamins, are required for yeast metabolism and growth. These minerals are cofactors of numerous enzymes [75].

Sulphur is required for the synthesis of cell proteins, vitamins, and certain co-enzymes such as co-enzyme A. Phosphates affect energy transfer and can inhibit nitrogen uptake when deficient. The presence of calcium improves yeast propagation and settling behaviour, magnesium supports carbohydrate metabolism, and iron and copper, in small amounts, have a positive effect on

respiratory metabolism. Zinc promotes protein synthesis, cell proliferation and, as a component of alcohol dehydrogenase, accelerates sugar breakdown. Potassium likewise supports cell growth, protein synthesis, and activates the enzymes of glycolysis [2, 24, 97, 98, 99, 100, 101]. In addition, it has been reported in the literature that yeast cells take up increased potassium under optimal physiological conditions [102].

Growth substances, such as pantothenic acid and biotin, are equally beneficial for yeast life support [24]. Vitamins, especially B vitamins, play a major role as coenzymes. Thiamine B1 as a cofactor of carboxylase and pantothenic acid B5 as a building block of coenzyme A are particularly noteworthy [75].

Fermentation by-products

Since the wort constituents have a significant influence on yeast metabolism, the spectrum of fermentation by-products also depends on this [74, 103, 104, 105, 3, 75]. The alcoholic by-products, which the yeast excretes into the beer in addition to CO₂ and ethanol, include a large number of substances that can be divided into the following groups [75]:

- Higher alcohols
- Esters
- Carbonyl compounds
- Sulphur compounds
- Organic acids
- Polyhydric alcohols

Those groups influence the aroma and sensory impression positively as well as negatively and cause a significant difference in taste between wort, green beer and beer [7, 24, 75]. The most important groups include esters and higher alcohols. Their formation can only be increased or decreased by process control and yeast strain selection. Young beer flavours, such as diacetyl or acetaldehyde, are removed from the beer during and by means of fermentation metabolism. In order to achieve a pure taste and an aroma profile corresponding to the beer type, a certain ratio between flavour substances and a low content of green beer flavour substances is aimed for [1]. Young beer flavour substances serve as indicators of the beer's degree of maturation [1, 106].

The higher alcohols make up the largest concentration fraction of fermentation by-products and can contribute to ester formation. They are subdivided into aromatic and aliphatic alcohols. They encompass aroma impressions from alcoholic and solvent-like to rose-like. The α -keto acids necessary for formation originate from the catabolic trans- and deamination reactions of amino metabolism or sugar degradation and the associated anabolic reaction [20, 63, 2, 107]. Thus, the resulting higher alcohols can be assigned to the original amino acids: 2- and 3-methylbutanol, for example, are due to isoleucine and leucine, whereas iso-butanol and n-propanol are derived from valine and threonine [74]. The production of higher alcohols by yeast is related to sugar and amino acid uptake. The higher the uptake, the more higher alcohols are formed. Since amino acid metabolism is directly related to yeast growth, increased yeast growth can be expected to result in increased concentration of higher alcohols [108, 109].

The main component of the aroma profile of the finished beer is formed by the volatile esters. These are composed of acetic acid and fatty acid esters and originate from the yeast's own fatty acid metabolism. The intracellular enzymatic reaction here is based on alcohol acetyltransferase, which transfers the acetyl/acyl group of an acetyl/acyl CoA to a higher alcohol and esterifies it with an acid [110]. A comprehensive summary of the factors influencing ester formation can be found at *Verstrepen et al.* [111]. The final concentration of esters is significantly influenced by the yeast strain and the fermentation temperature. In addition, the original wort content, lipid and nitrogen concentration, wort aeration, pitching method, and pressure conditions influence the ester composition [63, 111]. Consequently, the choice of fermentation parameters is crucial. Ester formation can be suppressed by an increased content of unsaturated fatty acids. More yeast cells are formed as a result, which causes the utilization of energy-rich compounds such as the co-enzyme CoA. This is then no longer available for ester formation [24]. The formation of esters is also reduced if there is low osmotic pressure, a lot of alcohol or already a lot of carbon dioxide in the fermenting wort [112, 110].

Since sulphur also enters into yeast metabolism, sulphur-containing by-products are formed, which are considered base young beer bouquet substances, but are degraded again within beer aging [1]. In the context of improved flavour stability, the synthesis of sulphur-containing amino acids and the resulting SO₂ content should be noted [24]. SO₂ protects against oxidation and also forms a masking effect. The ratio of methionine, biotin and pantothenic acid is crucial for the formation of volatile sulphur compounds. A deficiency of these or a greatly increased content of threonine, as an inhibitor of methionine synthesis, leads to increased hydrogen sulphide formation [24].

The formation and resulting concentration of vicinal diketones, diacetyl and 2,3-pentanedione, is particularly important as a maturation indicator of beer. The build-up and breakdown of these can be divided into three phases. Via pyruvate or the deamination of valine and isoleucine, the precursors α -acetolactate and α -acetoxybutyrate are formed during the amino acid synthesis of yeast metabolism and released into the green beer. A temperature-dependent non-enzymatic decarboxylation converts the precursors into diacetyl and 2,3-pentanedione. This reaction is accelerated at higher temperatures and lower pH values [1, 20, 63, 113].

3.2 Nutrient requirements

Since yeast uses wort as a nutrient medium during fermentation, it follows that the wort composition in particular controls yeast growth and fermentation quality in terms of nutrients and growth substances. Yeast requires assimilable organic carbon and energy sources, assimilable nitrogen compounds, essential minerals, trace elements, and vitamins such as biotin for cell proliferation under aerobic conditions. In addition, unsaturated fatty acids are essential for yeast supply under these conditions [3]. For example, zinc should be present at 0.10 – 0.15 mg/l and free amino nitrogen at least above 160 mg/l [7]. If there is a deficiency of zinc, fermentation proceeds sluggishly and more fermentation by-products are produced [7]. In particular, during the stationary – and the decay

Table 5 Important substances for yeast [7]

Substance	Concentration
Calcium	10 – 20 mg/l
Iron	positive / toxic in excessive amounts
Free amino nitrogen	> 160 mg/l
Manganese	> 40 mg/l
Zinc	0.10 – 0.15 mg/l

phase of yeast growth, increased amounts of undesirable secondary metabolites are secreted during autolysis [24].

A balance of the nutrient, growth and mineral supply of an average beer wort with regard to an optimum yeast supply was already prepared by Annemüller et al. [1]. Here, the respective surplus or deficit of nutrients was calculated for an input of 100 kg sucrose and a baker's yeast growth of 8.1 kg as yeast dry matter. According to this calculation, the assimilable nitrogen in the form of free amino nitrogen, the metal ions zinc and iron, and the vitamin pantothenic acid are present in insufficient amounts and thus limit yeast propagation.

For an optimal supply of yeast during fermentation, the substances listed in table 5 should be present in sufficient quantities.

Yeast nutrition can also be supported by introducing long-chain fatty acids. Since fatty acids are mainly excreted with the hot trub in conventional brewhouses, it is possible to improve yeast nutrition by retaining the hot trub. In particular, palmitic acid and linoleic acid are crucial for sufficient yeast nutrition and can also be introduced into the process, for example, by increasing lauter turbidity [47].

3.3 Yeast growth and physiological state

During fermentation, multiplication occurs to four to eight times the original cell number [63]. During this process, different stages are passed through. The different phases are distinguished on the basis of the physiological state of the yeast [24, 1]: Lag phase, exponential growth phase (log phase), stationary phase, decay phase.

The physiological state of yeast possesses a decisive influence on fermentation, yeast growth and pH drop [103]. Likewise, there is a relationship to the fermentation by-products produced and the sedimentation behaviour of the yeast. The terms viability and vitality are used to assess yeast condition. When deterioration occurs, cell death and associated autolysis sets in [114].

Viability

The term viability refers to the viability of yeast cells. This refers to the proportion of live and dead yeast cells and is expressed as a percentage [114, 115].

Vitality

The vitality describes the actual physiological condition of the yeast, since this also makes a statement about the activity or

the fermentation performance. The term vitality also refers to the ability of the yeast to live under stress conditions [116, 115]. The condition of the yeast depends on many different factors such as temperature, pressure, nutrient supply, yeast preparation, number of guides and age of the yeast cells [116].

Autolysis

In contrast to the metabolism of a yeast cell in a good physiological state is autolysis. This describes the self-digestion of yeast after cell death. In this process, the yeast's own enzymes break down the cell's own carbohydrates. In this process, the structure of the yeast cell is destroyed. The substrate is enriched with protein degradation products and amino acids, and excretion of the basic amino acids results in an increase in the pH of the beer. During excretion, yeast proteases and medium-chain fatty acids with their ethyl esters are also released [24, 7, 117, 118, 119].

3.4 Beer composition

The wort ingredients are metabolized by the yeast during fermentation. In addition to ethanol, carbon dioxide and the excreted fermentation by-products, unmetabolized wort ingredients remain in the beer. These beer constituents, selected as a continuation of the wort constituents described above, are listed in table 6.

Table 6 Beer composition [7]

Fraction	Unit	Concentration
Carbohydrates		
Fructose	g/l	0.1 – 0.2
Glucose	g/l	0.1 – 0.5
Saccharose	g/l	0 – 0.5
Maltose	g/l	2 – 3
Maltotriose	g/l	1 – 3
Protein		
Nitrogen compounds	ppm	700 – 800
α-amino nitrogen	ppm	80 – 150
Lipids		
Free fatty acids	ppm	0 – 0.5
Minerals		
Potassium	ppm	30 – 550
Sodium	ppm	40 – 50
Magnesium	ppm	100
Calcium	ppm	15 – 50
Copper	ppm	0.1
Iron	ppm	0.1
Zink	ppm	0.05
Manganese	ppm	0.15
Polyphenols		
Total polyphenols	ppm	150 – 200
Anthocyanogens	ppm	50 – 70
Tannoids	ppm	10 – 40

3.5 Beer quality

The quality concept of a beer comprises the totality of its properties. Consequently, a beer can be judged according to several quality characteristics and they can be found in microbiological, colloidal, foam and flavour stability [120]. These characteristics are a result of the fermented wort and therefore linked to process technology and fermentation by-products.

3.5.1 Taste stability

Taste stability is an essential component of a high-quality beer and here describes the property of a beer to retain the sensory characteristics of the fresh state until consumption [7, 104]. During beer production, the taste and aroma of beer are influenced by the raw materials, wort preparation, and fermentation [103]. In this process, the flavour and aroma of the finished beer is not stable and is subject to a natural and dynamic aging process. The formation and progressive degradation of beer constituents increasingly changes the flavour profile of a beer over time. The flavour changes are generally considered negative and are referred to as undesirable flavour profiles, so-called off-flavours [7, 121, 122, 72, 24, 123, 124]. During aging, the following sensory changes occur in addition to loss of recency [7, 121, 24, 103, 104]:

- Loss of fullness
- Increase in bitterness (lingering and astringent)
- Change in aroma profile
- Loss of hop character
- Decrease of ester aroma
- Reduction of phenolic note in wheat beers
- Loss of malt aroma in dark beers
- Development of an aging flavour

The aroma components relevant to aging are formed in the course of storage, primarily by oxidation reactions and under the influence of heat, oxygen and light [7, 72, 125]. Consequently, oxidation prolonging beer ingredients are of great importance for flavour stability. Likewise, the loss of some aroma components leads to a faster perception of the aging impression. The masking effect of some beer constituents is consequently lost. The flavour profile that develops thus depends on three factors: Formation of aging-relevant aroma substances, antioxidant-acting beer ingredients and masking-acting beer ingredients.

The formation of aging flavours can be attributed to the following reaction pathways [7, 24, 72]:

- Caramelization, Maillard reaction, and Strecker degradation.
- Oxidation of higher alcohols
- Oxidation of isohumulones
- Fat degradation
- Reactions of aldehydes
- Other reaction mechanisms

The resulting substances are considered to be of great importance for the aging impression [103]. Some of these com-

ponents can be used as indicator substances for thermal (heat) or oxidative (oxygen) stress [72, 125, 7].

Antioxidants are substances that cause a delay or a prevention of oxidation processes [126]. These reaction mechanisms include [105, 126]:

- Direct scavenging of oxygen
- Chelation: Binding of metal ions
- Prevention of chain reactions by scavenging the starter radical
- Prevention of radical chain reactions by interception of an intermediate radical

Typical antioxidant substances within the malting and brewing process include, for example, sulphur dioxide, phenolic substances, Maillard products and vitamins. Some of these are already present in the raw material or are formed during the process [7, 2, 105].

The aging aroma can also be masked by the formation of sulphite-carbonyl complexes. These complexes are reversible and not aroma active. The masking effect is lost if the aging carbonyls are removed from the complexes by oxidation of the sulphite to sulphate [103].

For a technological influence on the flavour stability, several possibilities can be found in the field of malt and wort preparation as well as filtration, bottling and storage of the beer [7, 127, 128, 73, 129, 72, 24, 124]. Here, the wort composition as the starting point for the overall flavour impression as well as the yeast must be considered above all [130].

3.5.2 Chemical-physical stability

After prolonged storage, especially at varying temperatures, filtered beer loses its clarity until a turbidity or sediment finally appears [22]. This tendency of the beer to form a so-called colloidal turbidity is referred to as chemical-physical stability. According to IUPAC, colloids are particles with a size between 1 nm and 1 µm [131]. Two different manifestations occur as beer turbidity: reversible cold turbidity between - 8 °C and + 5 °C and irreversible permanent turbidity [132]. Cold haze, which disappears again when the beer is reheated to 20 °C, is regarded as a precursor of permanent haze [132, 133]. The former occurs due to weak hydrophobic bonds and hydrogen bonds between the beer components, while permanent haze is based on oxidation and covalent bonds [134, 135, 136].

The resulting haze consists mainly of polyphenol and protein compounds [137, 138, 139, 140, 141, 142, 143, 144]. Polysac-

Table 7 Percentage composition of colloidal beer turbidity according to Gramshaw [139], Wainwright [147], Narziss [24], Rehmanji [148] and Knorr [149]

	Gramshaw [139]	Wainwright [147]	Narziss [24]	Rehmanji [148]	Knorr [149]
Polyphenols	17 – 55	15 – 75	–	ca. 17	30 – 45
Proteins	58 – 77	40 – 77	40 – 75	40 – 75	45 – 65
Carbohydrates	2 – 12	0 – 13	2 – 15	3 – 13	2 – 4
Inorganic components	2 – 14	1 – 14	1 – 14	1 – 5	1 – 3

charides and inorganic substances also cause turbidity, but play a minor role [139, 145]. The occurrence of turbidity is accelerated by external factors such as oxidation, temperature, heavy metal ions, agitation, light, and oxygen [146]. The percentage composition of a colloidal turbidity can be found in table 7.

This beer turbidity can be perceived visually as clear, opalescent or cloudy and can also be detected by measuring scattered light [22]. Predictions on the colloidal stability of a beer can also be made using so-called forcing methods. Here, the interplay of temperatures is exploited to induce permanent turbidity [22].

Colloidal stability can be positively influenced by various measures within the brewery. Starting with the selection of raw materials, such as the use of low-protein barley, through the brewing process, by means of low pH values and rapid fermentation, to the use of stabilizing agents, such as silicic acid preparations or PVPP (polyvinylpyrrolidone), in the cold area, it is possible to improve the chemical-physical stability [24, 150].

3.5.3 Beer foam and foam stability

Good beer foam is considered a decisive quality criterion [79]. This is attributed not only a visual, but also a sensory and technological significance. The foam crown acts as a protection against diffusion of carbon dioxide and oxidation of the beer ingredients, and consequently the beer's recency is retained in the glass for a longer period [7].

The beer foam generally belongs to the liquid foams [151, 152]. In this case, the disperse phase (CO₂) is finely distributed in the dispersant (beer) [151, 153]. The CO₂ is released when the beer is poured into a glass by falling below the solution equilibrium. As the carbon dioxide bubbles out, the surrounding air is entrained, so that the resulting foam consists of a mixture of released CO₂ and air. The liquid, which is also entrained, is now located as a beer film between the foam lamellae [7, 152].

The beer foam is fundamentally subject to physical processes in its build-up and decay. While the foaming of the beer takes place within a few seconds, the foam decay, depending on the type of beer, occurs exponentially over time [154]. Four processes are distinguished [7, 155, 156, 157]:

- Foaming
- Drainage
- Coalescence
- Disproportionation

In relation to beer foam, the term foam stability is of great importance. This describes the durability of the beer foam of a freshly poured beer. In general, foam durability is influenced by several factors both positively and negatively by technological influences

Table 8 Overview of foam positive and negative factors [24, 7, 152, 157, 161, 162, 163]

Foam positive	Foam negative
High molecular weight nitrogen compounds (10 – 60 kDa)	Low molecular weight nitrogen compounds (special hydrophilic amino acids)
Hop bitter compounds (iso-alpha acids and alpha acids)	Fatty acids (C6 – C12), neutral lipids, glycerides, sterols
Low molecular weight oligomeric polyphenols	High molecular weight polymeric polyphenols
Melanoidins	Alcohols
Glycoproteins	Esters, sulphites
Nitrogen, oxygen, air	Detergents and cleaning agents
Heavy metals	Proteinase A

and by beer ingredients [79, 7, 24, 158]. The areas of the beer production process starting with barley, malt, mashing process, lautering process, wort boiling, trub separation, fermentation, yeast up to storage have a decisive influence on foam stability [2, 7, 24]. For example, the physiological state of the yeast is directly related to foam stability [159]. Likewise, in addition to the technological parameters, the various beer ingredients affect the beer foam and its stability. These substances are divided into foam-positive (surface-active substances capable of forming elastic liquid films) and foam-negative (substances that interfere with foam formation or accelerate foam decay). Particles, for example, can also cause coalescence, the destruction of the liquid film [160]. Table 8 lists the factors influencing beer foam.

The beer foam can be measured by means of the NIBEM Foam Stability Tester or the Steinfurth Foam Stability Tester (SFT) [22]. In addition, the NIBEM Cling Tester can be used to determine the adhesion of the beer foam. The limit for good beer foam of a bottom-fermented, filtered beer is > 115 SKZ; below 100 SKZ, the beer foam is considered poor [2]. A list of other measuring methods, such as those according to Ullmann and Pfenninger or Ross and Clark, can be found at *Potreck* [162].

4 Conclusion/Summary

The wort and beer production is a process, which has to be well-aligned. Raw materials, technology and fermentation define the final beer. Every step in this process chain influences the next and has a influence on the wort composition which defines the nutrient supply of the yeast the therefore starting point for the fermentation. Especially the lautering system has a great impact on the wort composition, separating solid from liquid under consideration the different filtration and extraction principles. The decision for a novel lautering system has to be thoroughly evaluated, since it may change the whole downstream process and in consequence the beer. The conventional brewhouse process including the traditional lautertun is as state of the art well evaluated. The novel lautering system, the rotary disc filter, is still subject of research. Therefore a systematic comparison of worts and beers was carried out, in order to evaluate the differences between the lautering processes and their impact on the finished beer under identical raw material conditions. This comparison will be examined in the next article.

5 References

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Received 18 September 2023, accepted 4 October 2023