Influence of Lauter Turbidity on Wort Composition, Fermentation Performance and Beer Quality – A Review

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ABSTRACT

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This review paper covers a variety of aspects concerning lauter turbidity and wort clarity that have been published in the past decades. The components of wort which are connected to an increased lauter turbidity, such as lipids and long-chain fatty acids, are presented as well as how the further steps of wort production, i.e. wort boiling and clarification, have an impact thereon. Besides the influence of lauter turbidity on wort quality, technical aspects affecting lauter turbidity are discussed by comparing different lauter systems such as lauter tun, mash filter and strainmaster. It is further highlighted, how lauter turbidity and its components influence fermentation performance and yeast vitality. Finally, the consequences of increased wort turbidity for the resulting beers in terms of flavour quality, flavour stability, non-biological stability and foam stability are described.

Key words: Fermentation, lipids, long-chain fatty acids, mash separation, wort clarity, zinc.

Introduction

Beside other process steps in wort production such as malting[91], milling[14,54,83] and mashing[13,68,91], mash separation is most important in determining wort composition. It is generally considered as being the major bottleneck in practical brewhouse operations.[29,40] Wort turbidity is a well known indicator associated with the quality of the resulting wort and therefore is of outstanding importance.[29,59,70,78,79,92,111]

Lauter turbidity is mainly influenced by raw materials, lauter equipment and lauter procedure, in particular the height of filter bed, turbid wort pumping, raking, sparging and speed of lautering. The subject of this paper is limited to wort turbidity which is influenced by the technical aspects of the lautering procedure, while raw material derived turbidity[83] is not considered herein.

Lauter turbidity and lipids

Many authors have reported a correlation of wort turbidity to an increase of lipid substances in wort, particularly of long-chain fatty acids.[2,29,35,36,51,56,60,74,76–78,91,101,104] The content of long-chain fatty acids, and more particularly of linoleic acid in wort, is assumed to correlate in a partly linear fashion with EBC turbidity units.[29,91] However, this correlation could not be proven for small- and middle-chain fatty acids.[93] In general, in terms of long-chain fatty acids of wort, palmitic acid (C16) and linoleic acid (C18:2) are of major importance, while oleic acid (C18:1), linolenic acid (C 18:3), stearic acid (C 18), and others play only a minor role.[6,57,68,95]

The lauter step is assumed to be the most important step in the reduction of total long-chain fatty acids throughout the brewing process, whereby a reduction of more than 90% related to the total content in mash can be achieved.[27,34,37,50,68,72] Within the lauter process there is a correlation between intensity of raking (and therefore lauter speed) and wort turbidity.[68,74,79,90,91] Thus, according to Wackerbauer et al.[104] only 11% of the fatty acid content of mash could be found in the kettle-up (kettle-full) wort, while intensive raking caused 21% to remain. Similar to raking, sparging is assumed to increase turbidity as well as the content of unsaturated fatty acids, which might be adsorbed to particles.[91,103,104]

Wort boiling

During wort boiling[5], which causes hot trub formation and whirlpool operation leading to hot trub separation, a major reduction of free fatty acids takes place due to adsorption to the coagulum with the total amount of fatty acids remaining unchanged.[51,52,68,91] More specifically, the reduction of free long-chain fatty acids is in the range of 70–90% during boiling depending on their chemical properties, e.g., the number of double bonds.[104] In fact the major part of lipids (75–85%) already precipitate during heating of wort[29] since a coagulation seems to already take place in hot wort prior to boiling. To a minor extent fatty acid reduction during boiling is also caused by evaporation[58] and oxidation to degradation products[68].

Wort clarification

Although the majority of the lipids are removed during boiling, higher levels in sweet wort (kettle-up) also caused higher concentrations in cast wort. However, the levels did not differ that much afterwards.[47] Similarly, Eils reported that fatty acid contents in worts after whirlpool were comparable, due to an efficient hot trub separation, even if the lauter worts contained variable concentrations.[32] According to Graf[35], an efficient removal of hot trub and cold

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trub seems to decrease the difference between turbid and clear lautering in long-chain fatty acid concentration without eliminating it completely. Further effects of cold trub removal on beer quality are highlighted in more detail by Dickel et al.[23,24] For turbid kettle-up worts, separation problems in terms of precipitation and sedimentation of hot trub occurred during whirlpool operation.[80,90,91,111] The more turbid the kettle-up wort, the higher the trub content of wort and the worse the separation in whirlpool, leading to higher extract losses.[12,22,111,112] Even if the same fatty acid content was obtained after the whirlpool operation, different fatty acid contents combined with oxidative/auto-oxidative reactions during lautering (e.g. oxygen in sparging water) or wort boiling might lead to an increased formation of degradation products and therefore lower flavour stability.[1,21,27,32,73,100] The influence of the thermal load during wort boiling (boiling time, evaporation rate etc.) and clarification in terms of carbonyl formation were recently highlighted by Morikawa et al.[67] and Osamu et al.[82]

Finally, due to the extensive depletion during the brewhouse procedure only 1.0–2.6% of total lipids and only 4.1–7.6% of free fatty acids related to malt reach the kettle-up wort,[52] while only 0.1–3.0% of malt lipids reach the pitching wort.[33]

Further aspects of wort quality

Besides lipids and fatty acids, turbid worts contain more high molecular protein complexes, or protein-polyphenol complexes, which cause a lower bitter substance yield during wort boiling and an intensified precipitation of colloids which adsorb bitter substances.[90,111,112] Extremely turbid worts were observed to have a higher raw fiber and total nitrogen content while no significant influence on total carbohydrate and α-glucan content could be detected.[90] In contrast to this, Biermann[12] observed increased polyphenol and carbohydrate contents of wort as a consequence of an increased input of malted barley cell wall components and other disperse particles.

In terms of the content of solid particles in wort the opinions differ. While Narziß and Weigt[79] found no correlation between wort turbidity and solid particle content, Eils[32] could observe an increased solid content in kettle-up worts due to turbid lautering. It was shown that a high solid content in kettle-up wort was an indicator of high linoleic acid content in wort.[91] Moreover, insufficient starch conversion (iodine test) was observed in turbid worts.[74,90] According to Schur and Pfenninger[90] lauter turbidity had only minor influence on wort composition in terms of metals such as calcium, iron, copper and zinc. In contrast to this, Eils[32] observed increased zinc concentrations in more turbid kettle-up and pitching worts. Indeed, most of the zinc originally derived from malt[45] was removed during lautering or precipitates with trub during wort boiling and cooling later on.[53,55] In particular, zinc was found in mash at mashing-in in a concentration of 1.2–1.5 ppm, after mashing-in at a concentration of 0.37–0.56 ppm, while after lautering only 0.07–0.16 ppm was found in kettle-up wort, due to absorption to spent grains as well as dilution due to sparging.[19,53]

From an economic point of view, fast lautering due to intensive raking with low extract content in the post runs and in spent grains causes a high brewhouse yield.[43,90] Cost comparisons of different lauter systems were provided by Narziß et al.[76] and more recently by Andrews[4].

Technical aspects and lauter systems

In 1986, Dufour et al.[29] published a comparison of different mash separation techniques showing the following differences. While the filtration times increased in the order: mash filter (75 min), strainmaster (110 min) and lauter tun (180 min), the wort turbidity decreased in the same order (mash filter: 300 nephelometric turbidity units (NTU); strainmaster: 160 NTU; lauter tun: 30 NTU). The ability to separate fatty acids from mash and therefore lower wort turbidity also depends on the lauter technique applied and in this case the lauter tun was a bit ahead of the strainmaster, with both being much more efficient than a mash filter.[51,91] Accordingly, Wackerbauer et al.[102] could not detect a significant difference between lauter tun and strainmaster. The differences observed might be because of the application of finer grist with modern mash filters causing higher fatty acid content in the resulting wort compared to older mash filters with coarser grist.[32] Moreover, Dufour et al.[29] found 2.5-fold increased fatty acid content in mash filter worts compared to lauter tun worts. However, with all systems a reduction in total fatty acids by more than 90% (related to mash) can be achieved.[68] According to Eils[32] the amount of hot trub varies due to the lauter technique and while around 600–900 mg/L were found for a lauter tun, the amount for a conventional mash filter was in the range of 1,400–1,650 mg/L. The amount of solid particles influences the amount of hot trub, fatty acids, coagulable nitrogen compounds, and hop utilization.[32] Further, the particle content of kettle-up wort depends on the grist composition and the lauter method and while a modern lauter tun can reach a value of approximately 35 mg/L, mash filters reach a solid particle content of below 80 mg/L.[32] According to Schlecht[89] a solid particle content of up to 120 mg/L is acceptable, while Stippler et al.[96] recommended a limit of 100 mg/L. More recent investigations say that modern lauter tuns and latest mash filters produce bright worts with a content of solids of below 50 ppm.[7]

Lauter tuns

For lauter tuns the duration and efficiency of turbid wort pumping as well as the construction of the raking machine are important. In order to obtain bright lauter wort a maximum raking speed of 3 m/min (tip velocity) and a raking height of not lower than 5–8 cm above the false bottom were recommended.[71] The raking machine should contain a sufficient number of knives and should be lowered gently when in operation.[71] Besides raking, if a false bottom with gaps of greater than 0.8 mm and a larger free flow area was applied, worts of higher turbidity were obtained.[74] According to Jones et al.[47] the height of the filter bed makes a difference and deep-bed lautering was more effective in lipid removal than shallow-bed lautering. A drawing-off of wort from the top layer of the pre-run, or compressing the spent grain bed, caused an increase in fatty acids in the kettle-up worts.[15,36,80,104]

Mash filters and strainmasters

According to Schuster[58] and Letters[91] mash filters exhibit very turbid lautering in the beginning (>3,000 NTU)[29] with a fast decrease in fatty acids, while when using a strainmaster their concentration decreases only after sparging. However, the total volume of wort contained 50% less fatty acids compared to mash filter lautering.[91] Accordingly, the mash filter worts contain 2.9 times more solids than strainmaster worts.[91] The increased turbidity of mash filter worts is due to the application of a polypropylene filter and turbulence caused by sparging.[71] Moreover, the compression during wort extraction causes an increased release of mash components.[15,58] Despite high solid particle amounts, higher iodine numbers were also observed during wort boiling due to thermal degradation thereof.[71] These phenomena may be lowered by an extended recycling of first wort at the beginning of lautering.[71] When comparing a mash filter with a lauter tun, Dufour et al.[29] found lower overall lipid amounts in the mash filter wort. This was due to the higher lipid contents in sparging draw-offs (in 1°P sparging draw-off: 10 (mash filter) vs. 43 ppm of lipids (lauter tun)) despite the higher initial lipid content in mash filter separation (272 ppm) vs. lauter tun wort (11 ppm).

Fermentation

Schur and Pfenninger[90] investigated 24 large-scale brews and concluded that turbid lauter wort caused a significantly faster fermentation than clear worts, and this was also observed for trub rich worts.[84,87,88,105] The reason for this might be that with increased turbidity more fatty acids are introduced to pitching wort which favours the fermentation.[48,49] On the other hand, a high wort turbidity might make yeast stay in suspension longer. Lipids such as unsaturated long-chain fatty acids and ergosterol present in turbid worts have a significant influence on the growth and metabolism of yeast.[2,11,15,16,20,48,85,86,97,108] Particularly, unsaturated fatty acids and sterols are important due to their involvement in building up a functional yeast plasma membrane. Their presence in the membrane allows a correct cellular exchange between the cytoplasm and the external environment.[29] When supplementing yeast with unsaturated fatty acids such as linoleic acid, a greater yeast biomass resulted as a consequence of greater yeast activity and growth.[20,42,97] Linoleic and linolenic acid, as well as other polyunsaturated fatty acids, cannot be synthesized by *Saccharomyces cerevisiae* itself, but can be taken up from the medium.[6,18,66,86,97] However, yeast can synthesize palmitic and oleic acid in the presence of oxygen.[57] The unsaturated fatty acids appear to partially supplement the oxygen requirements of yeast and support the biosynthesis of sterols.[2,15,85] A high or very low lipid concentration causes an increased peak concentration of vicinal diketones during fermentation.[17] On the other hand, it was reported that lipid rich worts reached the diacetyl maximum earlier and degradation was faster.[91] Moreover, fatty acids have an influence on the ester synthesizing membrane-bound enzyme systems.[57,109,110] Increasing the content of unsaturated fatty acids in wort appears to be responsible for decreasing ester content, particularly of ethyl acetate in the resulting beers.[98,99] The presence of unsaturated fatty acids causes an increase in the uptake of group I–III amino acids and therefore an intensified formation of higher alcohols.[17,39,91,97] Similarly, according to Schuster[91] amino acids and glucose are taken up more quickly by yeast if wort contains a high fatty acid concentration. Finally, the described effects lead to a more intensive and significantly faster fermentation.

On the other hand, it was observed that bright worts have detrimental effects on fermentation.[46,62] The reason for this might be that the little or no trub carry-over to the fermentation tank minimizes the physical and nutritional benefits of trub needed for proper yeast growth and adequate fermentation performance.[53] According to Klopper et al.[50] the adsorption of fatty acids to hot trub during wort boiling and its removal in whirlpool operation is probably the explanation of fermentation problems of too brilliant wort filtration.

Beer quality

It is generally accepted that lauter turbidity is of outstanding importance in terms of beer quality.[78,79,111] Particularly, the importance of a clear lauter wort has often been emphasized.[59,70,92] Nielsen[80] summarizes the undesired components of turbid worts as follows: lipids which are believed to contribute to beer staling[6,28,63,94] and foam deterioration[6,94,107]; anthocyanogens derived from malt which cause a decrease in the non-biological stability of the finished beer[61], with the content of anthocyanogens in wort depending on the contact time of wort with grist; flavour compounds which directly affect the flavour quality; and starch since it affects both the biological and non-biological stability adversely.

Filterability

It was reported that more turbid worts led to a decrease in filterability as well as to centrifugation issues with the resulting beers.[32,87,90]

Flavour quality

According to Sommer[93] the influence of wort turbidity on beer quality is often overestimated. For example in his investigations fast and turbid lautering did not lead to a deterioration of flavour quality of the resulting beer.[111] In the extensive large-scale trials mentioned previously, Schur and Pfenninger[90] evaluated the influence of different lauter regimes (turbid, clear) and lauter durations (long, short) on the flavour quality of the resulting beers. Related to lauter turbidity and duration they found the following order with decreasing sensory quality of the fresh beers: "turbid/short", "turbid/long", "clear/short", "clear/long". When the same beers were aged for 5 weeks at 25°C the order was as follows: "turbid/long", "clear/short", "turbid/short", "clear/long".[90] In contrast, Mück[68] reported a negative influence of turbid lauter worts connected with high fatty acid amounts prior to wort boiling and high oxygen content on beer flavour and observed an unpleasant bitterness which most probably did not depend on fatty acids. Here, the influence of turbidity seemed to be bigger than that of oxygen. In contrast, Whitear et al.[106] explained that the effect of lipids was overestimated and weighs much less than the oxygen pick-up during wort production. When adding spent grain press liquor to wort, to reach a final value of 190 mg/L of lipids, they observed a marginally better flavor stability in the resulting beers than in the controls. A detrimental effect of very turbid worts on flavour development was also reported by others.[64,81,88] Moreover, beers resulting from fermentation of turbid worts showed a decreased ester content, particularly of ethyl acetate,[98,99] and an increased formation of higher alcohols[17] as discussed above. Some authors indicate a lower bitter substance yield due to high wort turbidity[32,90,111] due to a higher presence of protein or protein-polyphenol complexes[111] rather than due to an increased lipid content in wort.[91] On the other hand, Havenainen et al.[2] noted an onion-like flavour in beer originating from low-fatty acid worts. Considering solids, it should be mentioned that a solid particle content of 500 mg/L or below is assumed not to be critical in terms of flavour quality and bitter substance yield.[112] According to Schur and Pfenninger[90], higher pyruvate and lower acetaldehyde concentrations may occur in beers resulting from turbid worts, but lauter turbidity has only a minor influence on the following: diacetyl, 2,3-pentanedione, ethyl acetate, isoamyl acetate, ethyl caproate, β-phenyl ethyl alcohol, glycerol, colour, attenuation degree, pH value, gushing properties, viscosity, reduction potential, CO_2, nitrogen compounds, anthocyanogens, phosphate and calcium.[90]

Flavour stability

Turbid worts cause problems in terms of flavour stability,[3,8,68,88] even when there was an intensive treatment of cold wort (filtration) afterwards.[111] In connection with turbidity, fatty acids, which are estimated to be the only part of lipids being flavour-active in bottled beer, and particularly, unsaturated long-chain fatty acids, are of importance since they are the only ones reacting with oxygen.[9,103] More specifically, linolenic acid reacts 3–4 times faster than linoleic acid and the latter 30 times faster than oleic and palmitoleic acid and fatty acids bound as esters react up to 50% slower than the corresponding free acids.[64] In contrast, the oxidation of saturated fatty acids is meaningless due to the low reaction rate.[26] More specifically, fatty acids are assumed to be responsible mainly for the formation of epoxy and trihydroxy-acids, which are staling precursors, and have an increased solubility in wort and reach the final beer.[44,65,74] Linoleic acid is an important component of wort turbidity and is assumed to be a precursor of *E*-2-nonenal at the same time, thus being detrimental to flavour stability.[2,26,28,50] Besides *E*-2-nonenal, in turbid worts the content of other carbonyls such as *E*-2-butenal, iso butanal, iso valeral, hexanal, and *E*-2-octenal, was increased, with *E*-2-butenal being an excellent indicator for beer ageing according to Graf.[35] He concludes that turbid lautering has negative consequences for flavour stability, since fresh beers were already higher in carbonyls (162 vs. 100%) which further increased during ageing (193 vs. 162%).[35] The occurrence of carbonyls, due to the degradation of lipid substances, is of great importance in staling since they have a very low threshold in beer, partly in the sub-ppb range.[67,68] Additionally, there seems to be a correlation between the content of long-chain fatty acids and the organoleptic sense of staling.[60,68] Even though quantities are very small, the remaining lipids provide a considerable reservoir of precursors of stale flavour due to lipid degradation products.[6] In conclusion, many authors support that the removal of fatty acids from wort, as far as possible, is favourable for flavour stability.[31,41,72] According to Zangrando[112] clear lautering is obligatory to providing good flavour stability. On this point Schur and Pfenninger[90] partly disagree as they found that beers produced from extended lautering and very clear worts performed the worst in taste testings of fresh and aged beers.[90]

Non-biological stability

There are only few papers dealing with the effect of turbid lautering on the non-biological stability of the resulting beer. Turbid lautering is assumed to cause a lower non-biological stability[80,90] and the reason for this might be that turbid worts sweep along more anthocyanogens resulting in a higher affinity for the formation of haze in bottled beer.[80]

Foam stability

Lipids are known to adversely influence the foaming properties of beer by binding to foaming proteins.[10,38] Furthermore, it was observed that unsaturated fatty acids such as C16:1, C18:1, C18:2, and C18:3 are efficient foam destroyers, when added to beer in concentrations of higher than 0.6 mg/L.[52] In combination, they may be present in a concentration to cause an adverse influence on foam stability.[50,113] On the other hand, it is reported that the unsaturated C18-fatty acids showed only an effect with a 40-fold increase compared to their usual concentration in beer.[47] Further, a more detailed observation allowed the conclusion that partly phospholipids and particularly glycolipids depressed foam formation significantly, while the neutral lipid fraction had almost no effect on foam stability, even when added to beer at a concentration of 10 mg/L.[58] Byrne et al.[15] found a deterioration of foam stability after addition of spent grain liquids to fermenting wort due to high glycolipid concentrations. According to Schur and Pfenninger[90] and Anness and Reed[6], turbid lautering or lipids cause a slightly lower foam stability in the resulting beers. In contrast to this, Eils[32] reported that turbid lautering and/or higher contents of oxygen during lautering or lower intensity of wort boiling caused an increase of coagulable nitrogen in wort and of foam stability of beer. According to Schuster[91], when lipids extracted from spent grains were added to a fermentation the resulting beer foam was not negatively affected but rather was stabilized. Even after the third fermentation cycle no deterioration was detectable compared to the control. Thus, Schuster[91] concludes that lipids derived from turbid lautering do not have a negative influence on foam stability. Letters[58] offers an explanation for this: "the surface-active properties of lipids may be beneficial for head retention since they can suppress excessive fobbing during fermentation. Head positive substances, mainly protein derived, are concentrated in the fob and can be removed from the fob by precipitation. This may explain why worts with high lipid content, e.g. from a mash filter, can give a beer with better head retention than that produced from a low lipid content wort". Indeed, mash filters and strainmasters releasing relatively high levels of lipids in wort resulted in beers with better foam stability compared to controls produced with lauter tuns.[30] Greffin and Krauß[36] could not detect an influence of turbid worts drawn-off from the surface during lautering on foam stability. It has also been observed that beers resulting from hazy worts tend to gush,[51] which is in contrast to the findings of Schur and Pfenninger.[90]

Conclusions

As described in this review paper, mash separation and lauter turbidity have been studied by many research colleagues for decades and the topic is still being investigated. The ongoing interest in this field underlines the great impact that wort clarity appears to have on the further process steps of beer manufacturing and on the final product quality.

During the 1970s and through the early 1990s, many authors described the components of increased lauter turbidity, mainly lipids and fatty acids, and to what extent they originate from different lauter techniques. In this context most of the authors pointed out the positive influence of cloudy wort in terms of yeast metabolism and fermentation performance. At the same time, however, the adverse consequences of high lauter turbidity for the final beer quality, particularly for flavour and foam stability, were thoroughly discussed. Since the negative consequences seemed to outweigh, this led to the preference of high wort clarity, and this has been generally accepted among brewers until today.[25,69,75] On the other hand, some authors described fermentation problems and even an adverse final beer quality when worts were very bright.[2,46,50,62,90] This may be particularly important when adjuncts (e.g. rice) are used for brewing. Unfortunately, in many papers a reliable definition is missing regarding the terms "turbid" and "bright" wort, making a quantitative evaluation difficult.

Great efforts have been undertaken by the brewhouse suppliers over the last decades to technically improve the lauter equipment. Thus, the average lauter turbidity dropped tremendously, now reaching a value of roughly 10 EBC units when applying state-of-the-art technologies. Secondly, it has to be considered that yeast performance has been continuously improving in practical operations, thanks to intensified research and implementation of modern yeast management technologies. With these two aspects in mind, the question arises whether the threat of a quality loss, possibly originating from lauter turbidity, is nowadays overestimated. Since a proper fermentation is a premise for a high beer quality, it has to be questioned whether the today's lauter turbidity may be too low to provide a proper yeast nutrition. Therefore, it seems to be worthwhile to discuss a new statement of preferring a moderate lauter turbidity, within the range of lauter turbidities currently observed, instead of the minimum turbidity that is technically realizable today in order to provide proper yeast nutrition and to minimise adverse quality effects at the same time.

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