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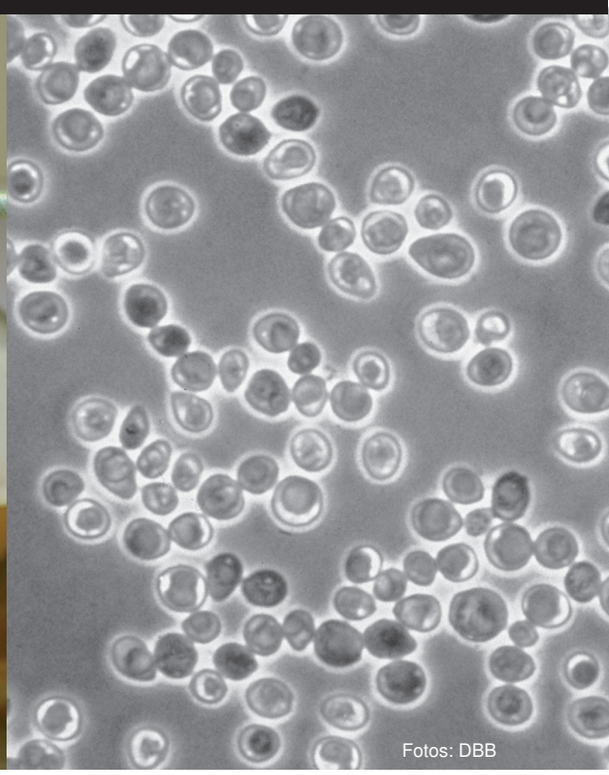

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The impact of dry hopping on selected physical and chemical attributes of beer

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Ludwig Narziß Award

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The impact of dry hopping on selected physical and chemical attributes of beer

The scope of this study was to investigate how incrementally increasing dosing rates for dry hoping up to 1500 g/hl with type 90 Cascade pellets affects selected chemical and physical characteristics of beer. To this end, 6 hl of pale ale was brewed on a pilot system. After primary fermentation, this base beer was split in 20 litre NC kegs in order to perform each dry hopping trial in triplicate. From these beers the variations of the following characteristics after dry hopping were investigated: bittering units, alpha acids and iso-alpha acids, humulinones, total polyphenols, flavanoids, iso-xanthohumol and xanthohumol, real extract, alcohol, pH value, foam stability (NIBEM and Steinfurth) and turbidity. In addition, the influence of the plant material from the hops on these selected characteristics was examined. For this purpose, dry hopping trials using 1000 g/hl of spent hop pellets sourced from hop extraction with CO_2 were also performed on the same base beer.
As a result of our trials, significant effects were observed with regard to the decrease in iso-alpha acids and foam stability, as well as an increase in humulinones, the pH value, real extract and total polyphenols in the instances where type 90 pellets were used for dry hopping. In particular, the decrease in iso-alpha acids appears to be linked to the presence of hop plant material. In contrast to the changes mentioned above, either behaviours of certain compounds remained unchanged or no clear conclusion was able to be drawn concerning the influence of dry hopping on the following: flavanoids, iso-xanthohumol, xanthohumol and alcohol content as well as the turbidity and the bittering units determined analytically.

Descriptors: dry hopping, bitter substances, polyphenols, foam stability, turbidity, pH value, real extract and alcohol content, spent hop pellets

1 Introduction

Dry hopping is an essential technique to produce certain beer styles such as pale ales, India pale ales (IPAs) and New England IPAs. Compared to lager beers, these top-fermented styles require the addition of significantly higher quantities of hops, not only in the brewhouse during the boil or the whirlpool rest, but especially on the cold side of beer production. The main reason to add hops at this point is to impart an intense and unique hop flavour which is a typical and important attribute of these ales. Since craft beer has gained in popularity in past years, regular recipes for these types of beers have been developed further, reaching their maximum with almost unlimited additions in the dry hopping process. In 2014, the Brewers Association reported that the top-selling American Imperial IPAs contained between 9.0 and 11.5 g/L hop material compared to just 1.0 g/L found in American light lager beer [9]. In 2015, the average hop dosage in US craft beer was estimated to be around 561 g/hl [12]. As a result, beers with more than 100 IBUs, extreme haze or sometimes even green-coloured foam have entered the market, raising controversial discussions among brewers and consumers about flavour, appearance and new ways to evaluate these beers. For the most part, standard scales for the sensory assessment of bitterness and official analytical methods are inadequate to characterise these beers appropriately.

Even moderately dry-hopped beers possess a complex matrix once the hops are added because this influences their non-volatile chemistry in various ways. The addition of hops on the cold side leads to an increase in certain bitter substances such as non-isomerized alpha acids, humulinones and xanthohumol [13, 18, 19]. They are extracted in different amounts depending on the ethanol content of the beer and the polarity of the substance(s) but also the individual dry hopping technique, the hop dosage and initial concentrations of the analysed components also play a role. On the other hand, iso-alpha acids, for example, usually decline after dry hopping and the extent of this drop also depends on their initial level [17, 19, 26]. After dry hopping, the composition of bitter substances in the beer is quite complex. Unfortunately, the analytical method employed to determine the bittering units in beer cannot distinguish between individual components in an appropriate way [4, 9] although breweries in many US states might be required to submit this IBU value in order to license new beers [17]. Besides, water soluble compounds (primarily the polyphenols in hops) are dissolved in dry-hopped beer [26] and may contribute to cold break formation during production. Consequently, the colloidal stability and the colour of beer may also be affected. Through the loss of certain foam-positive proteins due to dry hopping, the foam stability may also be negatively impacted [5].

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Recently, the enzymatic potential of hops was investigated. It has been demonstrated that hops contain amylases which can hydrolyse carbohydrates that are normally not available for yeast metabolism [2, 15]. Due to this effect, also called "hop creep", the additional fermentable sugars present lead to the formation of more alcohol and CO_2 if some yeast activity remains during or after dry hopping. Of course, higher temperatures and higher yeast cell counts support this reaction. In addition to the "hop creep effect", a small amount of fermentable sugars is introduced by the hops [25]. Dry hopping generally contributes to the quantity of real extract [2]. But if the hops are added while the enzymes and yeast are still active, they certainly contribute to the final degree of attenuation; therefore, the fermentable extract from malt is not the only source of extract to be considered. This kind of "secondary fermentation" was also observed as a problem with bottle conditioning. The enzymes introduced by dry hopping enable fermentation of these otherwise unfermentable sugars, causing gushing or excessive pressure in the package, posing a safety risk for consumers or generating complaints at the very least. Furthermore, the declaration of the alcohol content on the beer label may be inaccurate.

Some studies also report changes in the pH value and foam in comparisons of beers before and after dry hopping. Concerning the pH value, all of the studies show at least a slight increase after adding hops [20, 16, 25]. Reports regarding the effects of foam stability are contradictory, but most studies indicate a decline in stability after dry hopping [21].

Obviously, all these changes due to dry hopping do contribute to overall beer flavour, perception of bitterness and astringency. Moreover, aroma profiles are more pronounced once the hops have been added to the cold beer. After dry hopping, the concentrations of many volatile compounds change significantly depending on the extraction conditions, their interaction with yeast (such as biotransformation and adsorption to yeast cells) [14, 30], the glucosidase activity of the hops [11] as well as solubility, hydrophobicity, pH and the effects of stripping [10, 27, 14]. However, aroma analyses and tastings were purposely excluded from this study in order to exclusively focus on the changes in the physical and chemical attributes. These chemical and physical "secondary effects" of dry hopping have rarely been investigated and little has been published about them, although they might play an important role in the analytical evaluation of dry-hopped beers as part of a comprehensive overview to allow deeper insight into this hopping technique.

In order to know more about the impact of dry hopping on the non-volatile components of beer, systematic trials in pilot-scale with incrementally increasing dry hoping rates up to 1500 g/hl using type 90 Cascade pellets were performed. From these beers selected chemical and physical characteristics have been investigated.

2 Materials and Methods

2.1 Hop pellets

Table 1 provides an overview of the hop pellets utilized in this investigation and their analytical characterisation.

Table 1 Characterisation of the hop pellets utilised in the investigation

	Method [6]	Type 90 pellets	Spent hop pellets
Variety		US Cascade	German Perle
Crop year		2016 crop	2017 crop
Moisture content	EBC 7.2	9.1 %	7.3 %
Lead conductance value	EBC 7.5	5.6 %	0.9 %
Alpha acids	EBC 7.7*	5.0 %	0.2 %
Humulinones	EBC 7.7*	0.3 %	< 0.2 %
Xanthohumol	EBC 7.8*	0.3 %	0.6 %
Polyphenols	EBC 7.14	4.6 %	5.1 %
Flavanoids	internal method**	0.5 %	0.9 %

* the most recent international standards or pure substances were used for the calibration

** combination of EBC 7.14 (sample preparation) and EBC 9.12 (spectrophotometric analysis)

For dry hopping, US Cascade was chosen as it is the variety most commonly used in dry-hopped beers. Spent hop pellets from Cascade were not available since this aroma variety is not normally used to make CO_2 hop extract. However, some varietal characteristics are lost during processing anyway, and spent hops of the variety German Perle were determined to possess a composition typical of spent aroma hops after CO_2 extraction.

2.2 Base beer production

The base beer was produced according to Hopsteiner's pale ale recipe. The original gravity of the wort was 14 °Plato and was produced with a grain bill consisting of 80 % pilsner malt, 10 % carahell and 10 % Vienna malt. Mashing was carried out according to a *hoch-kurz* (German meaning "high-short") mash program followed by 70 minutes of wort boiling with three hop additions. The first addition took place at the beginning of the boil at which time 50 % of the total alpha acids were added, followed by another 30 % of the alpha acids after 35 minutes and finally 20 % of the total alpha acids were added 5 minutes before the end of the boil. The hop additions were calculated to achieve 60 IBU in the base beer prior to dry hopping. For each addition, US Cascade type 90 pellets from the same batch were used (Tab. 1). Wort boiling was followed by a whirlpool rest of 20 minutes and cooling to an initial fermentation temperature of 18 °C. Fermentation was conducted at atmospheric pressure with the TUM 540 yeast strain (from the Weihenstephan Research Center for Brewing and Food Quality). When an extract content of 3.5 °Plato was reached, fermentation was halted by cooling down to 0 °C. This base beer was used in all of the dry hopping trials described below.

2.3 Dry hopping technique (static)

First, the single hop base beer was brewed and fermented (refer to part 2.2). This green beer was the basis for subsequent dry hopping experiments conducted during maturation using hop rates of 0, 250, 500, 750, 1000 and 1500 g/hl. In addition, a test series was carried out using 1000 g/hl of spent hop pellets for

dry hopping. Each hop addition was performed using identical dosages in triplicate. The pellets were placed loosely into 20 litre NC kegs. One week of contact time between the hops and beer was chosen. The beer was stored at a temperature between 4 and 6 °C. The kegs were inverted twice during this period to mix the contents and improve extraction of the hop components into the beer. The kegs were equipped with shortened extractor tubes, so that after dry hopping, the beer could be transferred to 10 litre NC kegs without the cold break sediment and the majority of hop particles. All of the trial beers were stored at 2 °C for two weeks and each carbonated to a standard concentration of 5.2 g/l of CO_2. Subsequently, the unfiltered beers were bottled. The separated hop particle sediment in the 20 litre NC kegs was used for additional analyses to measure the losses of iso-alpha acids after dry hopping (refer to part 2.5).

2.4 Beer analyses

Table 2 shows the methods employed for the analysis of various hop components in beer as well as for the beer analyses. All analyses were performed within two weeks after bottling.

Table 2 Overview of methods employed for the analysis of hop components and beer

Methods	
MEBAK 2.9.6.3 [22]	Alcohol [% vol.], Real extract [% w/w]
MEBAK 2.13 [22]	pH value
MEBAK 2.14.1.2 [22]	Turbidity [EBC]
MEBAK 2.18.2 [22]	Foam stability acc. to NIBEM-T Meter [s]
MEBAK 2.18.4 [22]	Foam stability acc. to SFT-Foamtester [s]
EBC 9.8 [6]	Bittering units [IBU]
EBC 9.11 [6]	Polyphenols [mg/l]
EBC 9.12 [6]	Flavanoids [mg/l]
EBC 9.47 modified (HPLC)* [6]	Alpha acids, Iso-alpha acids, Humulinones [mg/l]
HHV 30 internal method (HPLC) [31]	Xanthohumol, Iso-xanthohumol [mg/l]

* the most recent international standards or pure substances were used for calibration

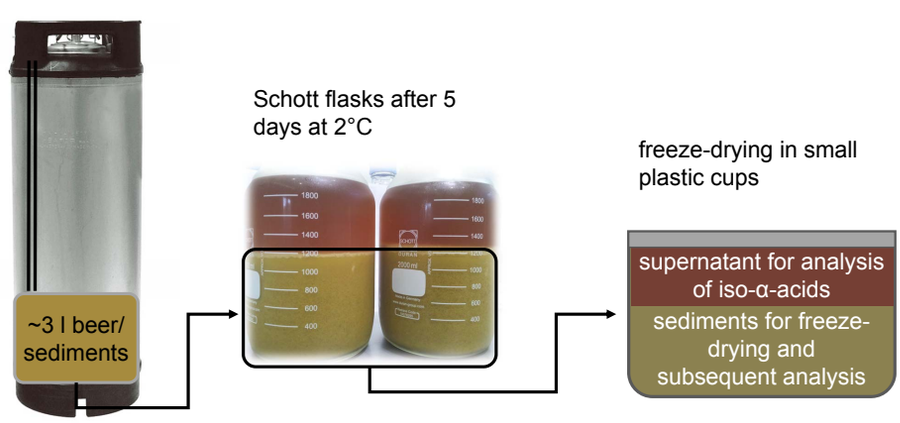

Fig. 1 Sample preparation for analysis of the sediment from the kegs

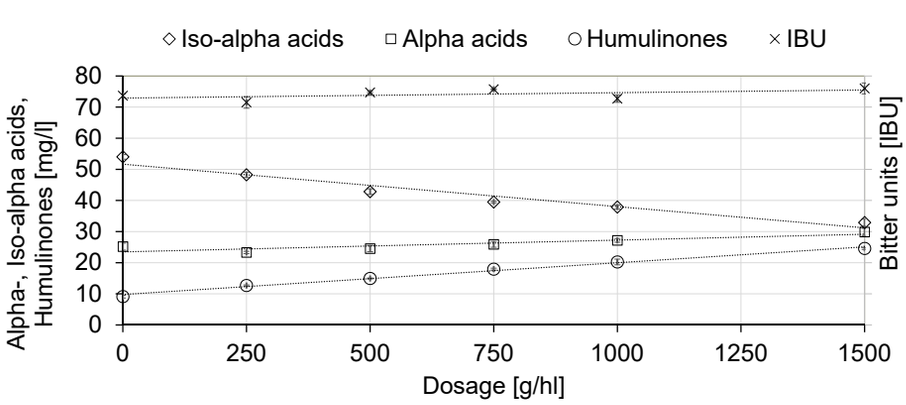

Fig. 2 Bitter substances and IBUs

2.5 Analysis of cold break material

HPLC analysis of the dry hopped beer samples showed that the concentration of iso-alpha acids decreased after the hops were added, a phenomenon which was both expected and observed. To determine the influence of the hop plant material and its adsorption on yeast cells, the cold break material including the separated hop particles in the 20 litre NC kegs were freeze-dried until reaching a water content of 5–7 % and further analysed. Sample preparation was carried out 5 days after dry hopping was completed in order to achieve a clear phase separation between the beer and particulate matter (Fig. 1). The content of iso-alpha acids in both the supernatant and the sediment was determined by HPLC. For this analysis the dosing rates of 500, 1000 and 1500 g/hl as well as the separate trial using spent hop pellets (1000 g/hl) were investigated. The supernatant was analysed according to EBC 9.47, the freeze-dried hop material according to EBC 7.11 [6].

3 Results and Discussion

Each trial and dry hopping dosage was done in triplicate, respectively, while each analysis was performed in duplicate.

3.1 Bitter substances and bittering units

In the trials using Cascade type 90 pellets, only the analytical bittering units remained almost unchanged in the range of 71.5 to 76.0 IBU, independent of the dosing rate (Fig. 2).

The lowest IBU was analysed for a hop dosing rate of 250 g/hl and the highest for 1500 g/hl. Compared to the initial IBU value of 73.7 in the base beer, variations from –2.2 to +2.3 were observed for the dry-hopped beers. Con-

sidering the existing internal analytical error of 1 IBU in the range from 13 to 36 IBU for the beers which were not dry-hopped [6], no significant changes could be observed in our trials, although an increase was expected [4, 19, 24, 26]. The other bitter components varied with increasing dosing rates. The iso-alpha acids dropped from an initial 54.0 mg/l down to 32.9 mg/l, resulting in only 61 % of the base beer's initial concentration left. The lower the dosing rates for dry hopping was, the higher the losses of iso-alpha acids were. Based on a calculation for each 100 g of type 90 pellets per hl of beer, 2.3 mg/l of iso-alpha acids were lost at the lowest dosing rate of 250 g/hl and only 1.4 mg/l at the highest (1500 g/hl). Other dosages followed an almost linear decline, resulting in a mean loss calculated to be 1.9 mg/l per 100 g/hl. As iso-alpha acids are the major contributors to sensory bitterness, a noticeable change in the sensory profile has to be assumed.

Concentrations of alpha acids and humulinones generally increase as more hops are added to the cold beer. In the case of alpha acids, a clear tendency has not been observed at low dosing rates but is apparent at higher dosing rates during dry hopping. In a comparison of the base beer and the highest dosing rate of 1500 g/hl, a maximum difference of +4.7 mg/l was determined for the alpha acids. It is known that the extraction of alpha acids in dry hopped beers is low, generally at levels below 10 % [8, 16, 23]. Furthermore, the initial value of alpha acids in the base beer was rather high. Both factors caused a slight decrease in this bitter substance, even if 1500 g/hl of type 90 pellets were added. Concerning the humulinones, an increase of 15.5 mg/l was detected. The final concentration of 24.6 mg/l was 2.7 times higher than that found in the base beer. The excellent solubility of the hydrophilic humulinones in beer has already been reported [20] and explains the very high extraction rate and therefore the relevance of this component in dry-hopped beers. Our trials also confirmed the recent reports regarding the lower extraction of humulinones at higher dosing rates [16, 20]. We obtained 1.4 mg/l of humulinones for the lowest and 1.0 mg/l for the highest dosage of hops per 100 g/hl. Considering the sensory impact associated with humulinones which make up approximately 66 % of the bitterness contributed by the iso-alpha acids [1], a concentration of 24.6 mg/l results in 16.2 sensory bitter units for the beer dry-hopped at a rate of 1500 g/hl. The difference between the base beer and the heavily dry-hopped beer is the 10.2 additional bittering units coming from humulinones. Considering the drop of 21.1 mg/l of iso-alpha acids mentioned above, about half of this loss in sensory bitterness is already compensated by the amount of humulinones extracted.

3.2 Polyphenols, Flavanoids and Turbidity

The initial polyphenol content of the base beer was 398 mg/l, reaching 496 mg/l for the beer dry-hopped with Cascade pellets at a rate of 1500 g/hl. This corresponds to a maximum increase of 25 %. A similar rise of 15 to 30 % was found for dry hopping trials at 4 °C by *Oladokun* et al. [25] although different hop varieties, dosing rates and a dynamic dry hopping technique was applied. Flavanoids remained practically unchanged in the range from 70 to 74 mg/l. No conclusion could be drawn from these findings and the dosing rate does not seem to affect the content of flavonoids. However, with respect to the total amount of polyphenols, a calculated average increase of 4.6 mg/l per 100 g/hl was documented for these trial beers. It should be noted that a very low extraction yield was observed, ranging from less than 1.0 % to just 14.2 % (lowest to highest dry hop dosage, respectively). An immediate reaction of polyphenols and their subsequent precipitation might be a possible explanation for the very low transfer rates. After precipitation, a considerable quantity of polyphenols might no longer be in solution and are therefore not able to be measured using routine analysis methods.

Since polyphenols and dry hopping itself (protein-polyphenol complexes, hop particulates, etc.) contribute to beer haze, the turbidity was also measured. Unfortunately, the analytical variation was too high to draw a reliable conclusion about turbidity and a possible link to the content of polyphenols or flavonoids, as it is given for other types of beer. During the analysis of the dry-hopped beers, it was observed that a certain sedimentation in the bottle and therefore handling prior to analysis influenced the results significantly. Standardized procedures for beers with inhomogeneous turbidity and particles are not available and therefore the method itself might not be applicable for unfiltered dry-hopped beers.

Finally, also xanthohumol and iso-xanthohumol were analysed. Starting at 0.5 and 2.0 mg/l respectively in the base beer, xanthohumol increased to 0.7 and iso-xanthohumol decreased to 0.1 mg/l. Therefore, no change was noticed for xanthohumol while an average decrease of 0.2 mg/l per 100 g/hl occurred with iso-xanthohumol. However, the very low concentration and corresponding lower analytical precision must be taken into account. Both compounds are present at such low concentrations that this rules out any sensory impact [3] or health benefits [7] and therefore is of minor interest for the type of beer in this investigation.

3.3 pH value

A maximum difference in the pH value of 0.4 was observed in a comparison of the base beer and the highest dosage of dry hopping. Despite the rather high initial pH of 4.9 measured in the base beer, each hop dosage resulted in a very consistent increase of 0.03 for every 100 g/hl. *Maye* et al. [20] reported a figure of 0.036 per 100 g/hl of hops added. Our results are also in line with those of *Lafontaine* et al. [16], who found a linear increase of 0.14 per 386 g/hl (or 0.036 per 100 g) independent of hop variety and beer style. Furthermore, Oladokun et al. [25] observed an increase that was even dependent on the temperature. All other studies referenced here measured the initial pH values which were lower. On the basis of these observations, we conclude that the pH value rises in any case, once a beer is dry-hopped. We consider this pH increase to be a disadvantage, primarily because of less microbiological stability in beer [29]. The increase in pH is partly driven by the vegetative material, also due to the fact, that an increase was observed when adding spent hop pellets from a CO_2-extraction (+0.15 units for a dosage of 1000 g/hl compared to 0.30 units in case of pellets type 90).

3.4 Real extract and alcohol content (by volume)

The real extract covers any soluble substance which contributes to the density of the beer. By adding hop pellets to beer, many

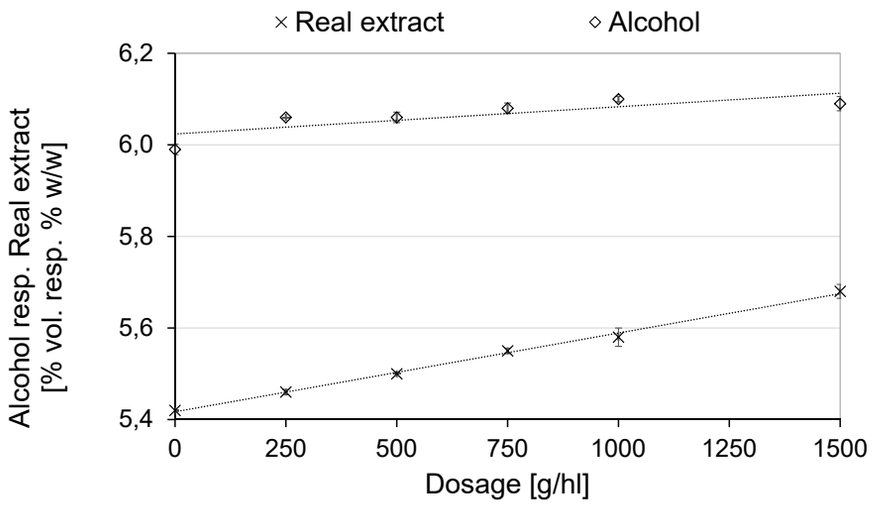

Fig. 3 Real extract and alcohol content

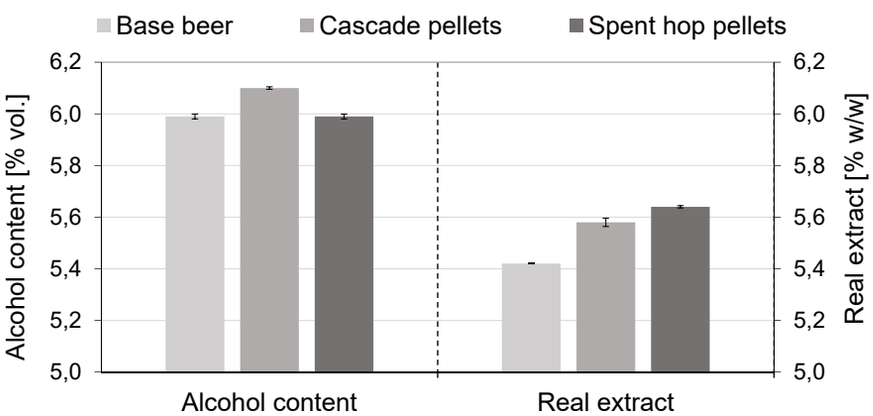

Fig. 4 A comparison of alcohol and real extract in the base beer only, with type 90 pellets and with spent hop pellets (both 1000 g/hl)

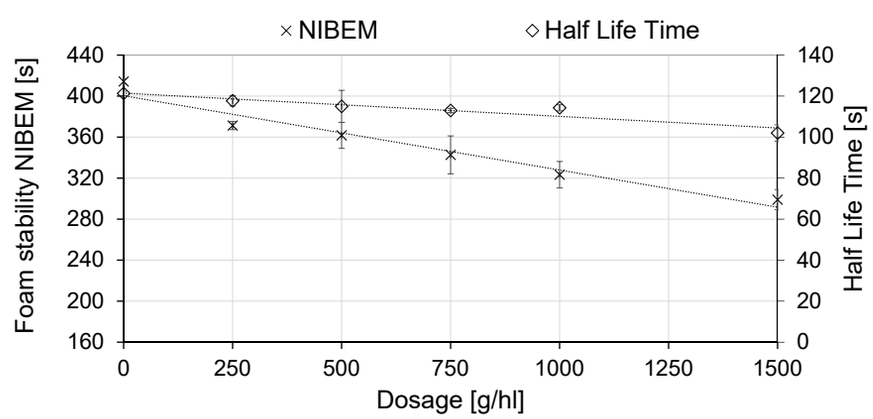

Fig. 5 Foam stability acc. to NIBEM and Steinfurth (0–1500 g/hl for type 90 pellets)

soluble substances dissolve in the beer and increase this value. Figure 3 shows the real extract and alcohol content depending on the quantity of type 90 pellets used for dry hopping.

Overall, the real extract increased by 0.26 % w/w in conjunction with the highest hop dosage and by 0.017 % w/w per 100 g/hl. Lafontaine et al. [16] observed almost the same function of real extract and dosing rates for dry hopping with a linear increase of approx. 0.07 % w/w for 386 g/hl (0.018 % w/w per 100 g/hl, respectively).

Alcohol content remained almost unchanged and the additional extract from dry hopping was not further metabolised. In our trials, dry hopping was done at low temperatures (4 to 6 °C), conditions which are not optimal for strong enzyme and yeast activity. Furthermore, primary fermentation of the base beer was already finished. The additional real extract from dry hopping is complex in composition and only small amounts of fermentable sugars are introduced by the addition of hop pellets. Consequently, no alcohol was formed after the type 90 hop pellets were added to the base beer.

Both effects are more obvious if the results are compared with those obtained from the trials using spent hop pellets (Fig. 4).

Adding spent hop pellets to the base beer had no effect on the alcohol content. The "hop creep" effect was not observed, although the real extract was even higher if the results are compared for spent hops and type 90 pellets. Since spent hop pellets are treated with high pressure during supercritical extraction with CO_2, it can be assumed that enzymes are inactivated by this process. Therefore, no further formation of alcohol occurred through yeast metabolism. The slightly higher value for real extract in case spent hop pellets is most probably due to the fact that a different hop variety was used for this particular trial.

3.5 Foam Stability

The foam stability of all beers was analysed according to NIBEM and Steinfurth methods. Both methods showed a reduction in foam stability at higher dosing rates for dry hopping when using type 90 pellets (Fig. 5). For the NIBEM analysis, 10.8 seconds per 100 g/hl have been observed in average, whereas the half life time (HLT) of Steinfurth decreased by 1.2 seconds for each 100 g/hl of hops added. However, it has to be noted that foam stability still remained on a very good level even if dry hopping dosage was very high.

Comparing the results of type 90 pellets and spent hop pellets (both depicted in Fig. 6), the foam stability behaved differently depending on the method used to measure it.

With the Steinfurth analysis, almost no effect on foam stability was observed with additions of type 90 pellets. Surprisingly, the foam stability was higher through the addition of spent hops compared

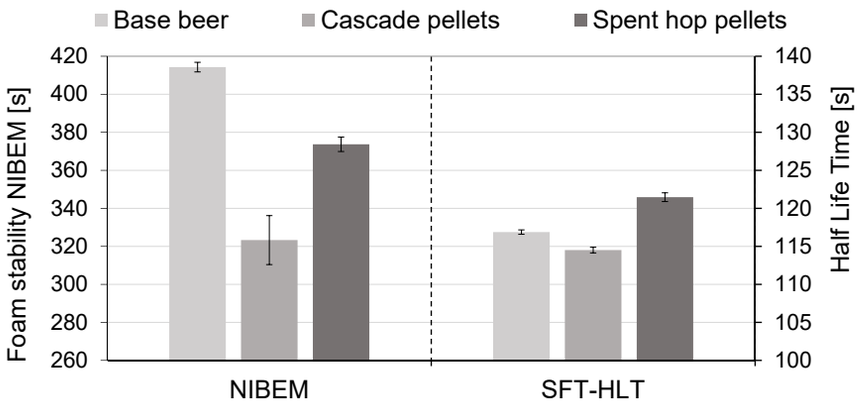

Fig. 6 Foam stability in the base beer only, with type 90 pellets and with spent hop pellets (both 1000 g/hl)

Table 3 Comparison of type 90 pellets and spent hop pellets (both 1000 g/hl)

	Type 90 pellets	Spent hop pellets
Increase	α-acids, Humulinones, Polyphenols, Extract, pH *Alcohol*	α-acids, Humulinones, Polyphenols, Extract, pH *Flavanoids, Xanthohumol*
Decrease	Iso-alpha acids, Iso-xanthohumol *Foam stability*	Iso-alpha acids, Iso-xanthohumol *Foam stability (NIBEM)*
No change or no reliable conclusion	IBU, Turbidity *Flavanoids, Xanthohumol*	IBU, Turbidity *Alcohol, Foam stability (Steinfurth)*

Table 4 Ratio of iso-alpha acids in supernatant and sediment at different hop dosing rates

Hop dosage [g/hl]	Factor of concentration *
500	7.5
1000	9.0
1500	8.7
1000 (spent hop pellets)	8.1
Mean value	8.3
Standard deviation	0.7

$$* \ concentration = \frac{c\ (iso\text{–}\alpha\ acids\ \ sediment)\ [mg/l]}{c\ (iso\text{–}\alpha\ acids\ decanted\ supernatant)\ [mg/l]}$$

to the blank sample. With the NIBEM method, a clear drop in foam stability was seen for type 90 pellets (on average, 91 seconds less) with a reduction of 41 seconds measured for the spent hop pellets. Although spent hop pellets not contain any foam-negative hop oils, waxes, lipids etc., the plant material itself exerts different influences on the method employed. With the NIBEM analysis, the slight drop might have also been caused by the precipitation of foam-positive proteins which are lost through complexation if interactions with polyphenols occurs. In addition, the loss of foam-positive iso-alpha acids after dry hopping might have contributed to the reduction in foam stability.

3.6 Comparison of type 90 pellets and spent hop pellets

For any other comparison not yet discussed between spent hop pellets and type 90 pellets, the following overview shows the different behaviour marked in italics, if given. As trials using spent hop pellets were only performed at a dosing rate of 1000 g/hl, the corresponding dosage of type 90 pellets was used for the comparison in table 3. In summary, the majority of the effects discussed follow the same general pattern, independent of the type of hop pellets used.

3.7 Analysis of sediment obtained from the kegs

To investigate the loss of iso-alpha acids after dry hopping, the supernatant and the sediment resulting from selected dosing rates were further analysed using HPLC analysis. By comparing the iso-alpha acid content in both samples, a factor for concentration was calculated on non-freeze-dried basis and listed in table 4. On average, 8.3 ± 0.7 times more iso-alpha acids were found in the sediment than in the supernatant. The same effect was seen for dry hopping with spent hop pellets. This demonstrates that within the given contact time, the plant material most probably adsorbs a certain amount of the iso-alpha acids, causing the major loss of this bitter component in beer after dry hopping. Of course, a certain amount of adsorption occurs on the yeast cells and the cold break material, which is also mixed with the particulate matter from the hops and partially contributes to this reduction [28].

4 Conclusion

Various dosing rates for dry hopping were investigated for their effect on the chemical and physical attributes of beer. Two types of pellets and varying differing dosing rates were utilised in the trials. The findings in this investigation indicate that dry hopping with type 90 pellets (Cascade) and spent hop pellets does not have a significant influence on the bittering units. The major bitter component in beer, iso-alpha acids, decreased by 1.9 mg/l per 100 g/hl when dry hopped with Cascade pellets. The loss of iso-alpha acids appears to be linked to adsorption on the plant material found in the sediments.

Depending on the dosing rate, the humulinone increase in beer dry-hopped with Cascade pellets varies from 1.0 to 1.4 mg/l per 100 g/hl. An increase in the alpha acid concentration was only observed at high dry hopping dosing rates. Furthermore, the total polyphenol content increases by 4.6 mg/l for each 100 g/hl, although this change is not linked to flavonoid content nor to turbidity levels in the unfiltered beer samples subjected to dry hopping.

The addition of type 90 pellets for dry hopping undoubtedly increases the pH value, whereas the foam stability declines. The

latter is not dependent on the specific analytical method applied and the stability of the foam decreased as more hops were added. The change in pH is in line with recent publications. In contrast to current publications, no increase in the alcohol content was observed; however, the real extract content increased proportionally with the dry hopping rate.

Although dry hopping is intended to impart aroma to beer, it was demonstrated that this hopping technique has a huge influence on the non-volatile matrix as well.

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