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PEER-REVIEWED ARTICLE

Dry Hop Best Practices: Using Science as a Guide for Process and Recipe Development

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ABSTRACT

Although Sapwood Cellars, located in Columbia, MD, is only 3 years old, we have been using the latest hop-related science as a guide to experiment with our dry hopping methods and procedures. Whether it is targeting a specific profile from a variety by dry hopping mid-fermentation or looking at ways to improve our hop oil extraction efficiency, the science has been instrumental in directing our focus. I spent 2 years researching a book published in 2019, *The New IPA: Scientific Guide to Hop Aroma and Flavor*, and continue to stay up-to-date on the latest papers focused on brewing hop-forward beers. This guide is a collection of what I have learned to date through the research, experience on the commercial scale, and tips from other experienced experts in the brewing industry.

What Are We Extracting During a Dry Hop?

The brewing process does its best to strip many of the volatile hop-derived compounds we are after from the finished beer. There are losses to steam, trub, yeast, and CO_2 produced during fermentation. We do our best to reduce some of these losses, like lowering our whirlpool temperature to 185°F (85°C) to retain impactful hop compounds such as linalool (5). Likewise, we utilize hop varieties that have a significant amount of survivable compounds, such as hop-derived esters, thiols, and oxygen-containing monoterpene alcohols, which do a better job at remaining in beer in their original or bioconverted state when introduced on the hot side (18).

However, even if you make all the right moves to retain compounds from the hot side, it is likely not enough to make the beer's hop character "pop" when the goal is a bright tropical and citrus IPA. The hot side additions provide a hop-saturated flavor base that actually needs additional layering of hop oils during or post-fermentation to really be assertive. Below is a review of some of the essential compounds we extract during dry hopping and which hop varieties may contain the highest concentrations of some of these volatile compounds (Fig. 1).

Note: Data for the various hop compositions of hydrocarbons, monoterpene alcohols, thiols, and hop-derived esters for this article provided by Yakima Chief Hops unless otherwise noted.

Hydrocarbons

Hydrocarbons represent the most significant percentage of a hop's total oil and are described as spicy, herbal, woody, green, and resinous once oxygenated. Hydrocarbons are also the most volatile during the brewing process. For example, myrcene has been tested to be reduced 50% by just 10 min of boiling and to be completely removed after a full 60 min boil (13). Although hydrocarbons are more likely to be stripped during the brewing processes than other compounds, recent research suggests they may be playing a role in heavily dry hopped hazy IPAs. For example, a 2018 study that compared myrcene levels in hazy commercial IPAs and West Coast IPAs found hazy IPAs retained much higher concentrations of this particular volatile hydrocarbon (9). The authors of the study suggest "haze in NEIPAs can act as a carrier and increase the concentration of nonpolar hop compounds" (like myrcene).

Because these green, astringent, and woody hydrocarbons can be retained in higher concentrations in hazy IPAs, it is worth experimenting by dry hopping with hops high in these compounds during active fermentation to help scrub and soften their profiles (if this is your desired outcome). For example, Sabro™ is high in two of the main hydrocarbons, myrcene and caryophyllene, and in my opinion can be a very dominant hop in terms of its intense coconut and woody flavors when used during dry hopping. Mid-fermentation dry hopping might be a way to reduce the variety's impact slightly while still allowing it to contribute to the complexity of the beer thanks to CO_2 production reducing the final hydrocarbon concentrations.

- Myrcene-rich hops: HBC 492, Pahto™, HBC 492, Centennial, Citra®, Sabro™, Bravo, and Mosaic®.
- Caryophyllene-rich hops: Talus™, Brewer's Gold, HBC 492, Centennial, Sabro™, NZ Motueka™, Brewer's Gold, and Chinook.
- Farnesene-rich hops: GR Tettnang, GR Spalt, Czech Spalt, Santiam, Sterling, GR Huell Melon, NZ Waimea™, Saaz, and NZ Green Bullet.

Monoterpene Alcohols

The oxygenated components of a hop (providing floral, fruity, and citrus flavors) represent about 30% of the total oil and are a very complex mixture of alcohols, aldehydes, acids, ketones,

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epoxides, and esters. Most important to brewers looking for intense tropical and citrus-forward IPAs are the terpene alcohols located in the oxygenated fraction of hops (examples: linalool, nerol, and geraniol). Despite representing a small fraction of the hop, they are more likely to remain in beer throughout the brewing process, especially during a dry hop. Monoterpene alcohols are less volatile than the terpene hydrocarbons (i.e., myrcene) discussed above. For example, one paper found that hydrocarbons have very low solubility compared with the fruiter oxygenated monoterpenes. Specifically, the paper found that monoterpenes containing oxygen in the form of a ketone, alcohol, ether, or aldehyde had solubilities 10–100 times greater than hydrocarbons (19).

- Linalool-rich hops: Bramling Cross, Crystal, Citra®, GR Tradition, UK Progress, Liberty, Loral®, Ultra, GR Hallertau Mittelfrüh, Nugget, NZ Dr. Rudi™, and Brewer's Gold.
- Geraniol-rich hops: Talus™, Brewer's Gold, HBC 492, Centennial, Sabro ™, NZ Motueka™, and Chinook.

Polyfunctional Thiols

The sulfur compounds in hop oil are extremely low at less than 1%, but their extremely low flavor threshold values make them an interesting flavoring variable. These sulfur compounds can be broken into four groups: 1) alkyl sulfides and polysulfides, 2) thioester, 3) sulfur-containing terpenoids, and 4) poly-

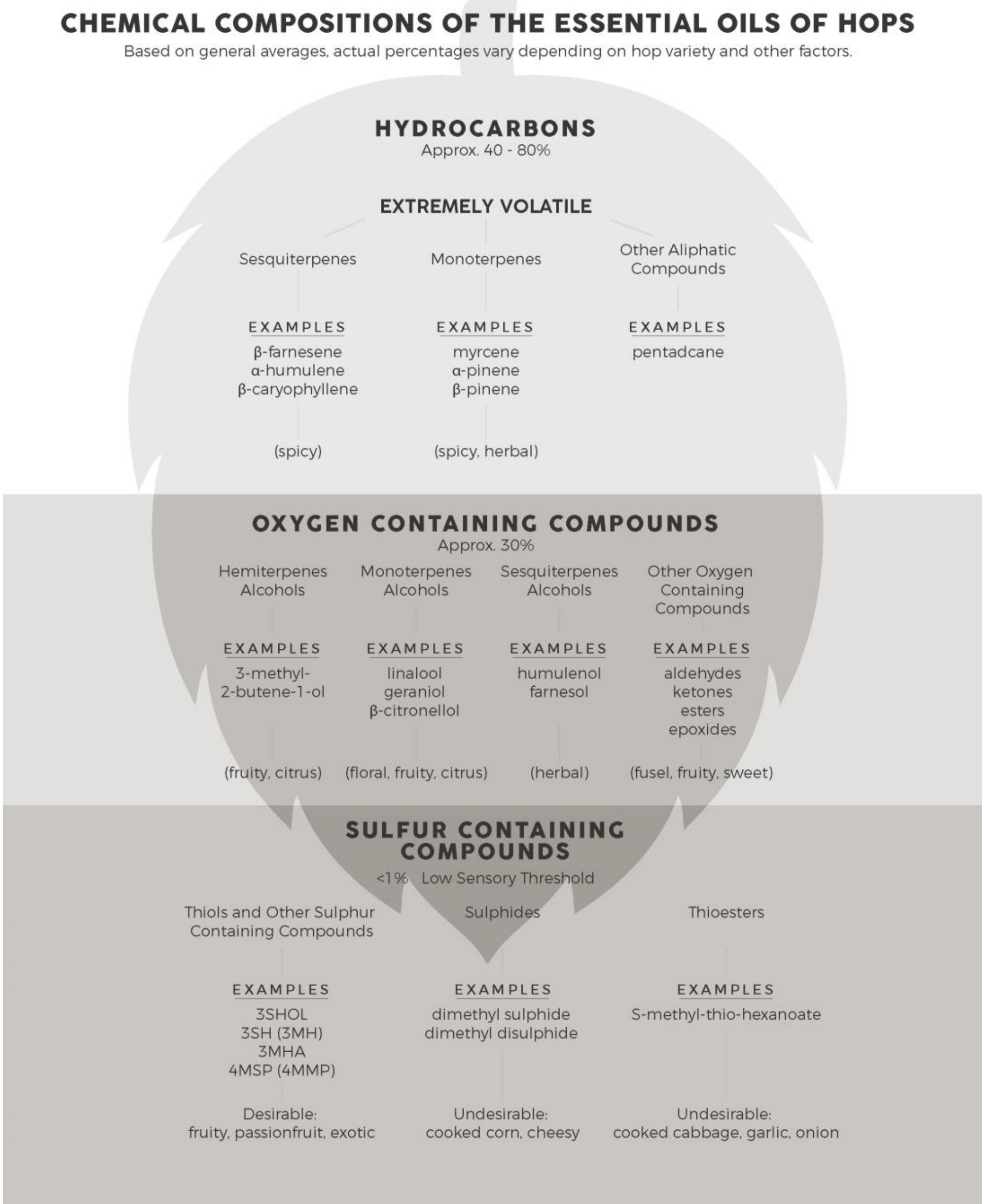

Figure 1. Overview of hop essential oils. © Scott Janish.

functional thiols. The polyfunctional thiols are the sulfur compounds in hops that are the most desirable in beer because of their potential for intense fruity flavors. The main thiols studied in hops are 3-mercaptohexanol (3MH), 4-mercapto-4-methylpentan-2-one (4MMP), and 3-mercaptohexyl acetate (3MHA), which is converted from 3MH. Hop-derived polyfunctional thiols are quickly becoming one of the most studied compounds in hops thanks to their low taste thresholds, allowing them to have significant impacts on heavily dry hopped beers. However, due to the challenges inherent in the analytical methods used to detect them (and their extremely low concentrations in beer) there are only a few labs in the world that have the capability to measure and study thiols.

- 4MMP has a blackcurrant and catty aroma (at high concentrations). Taste threshold 1.5 ng/L.
  - Hops high in 4MMP: Citra®, Simcoe®, Eureka!™, Summit, Apollo™, Topaz, Mosaic®, Ekuanot®, Galaxy®, and Nelson Sauvin (2).
- 3MH has a grapefruit/rhubarb flavor. Taste threshold 55 ng/L.
  - Hops high in 3MH: Pahto™ (very high), Columbus, Centennial, Millennium, Comet, Idaho 7™, Mosaic®, Bravo, Sabro™, Chinook, and Palisade®.
- 3MHA has a passionfruit flavor (converted from 3MH). Taste threshold 4 ng/L (14).

Hop-Derived Esters

Isoamyl isobutyrate, methyl geranate, and 2-methylbutyl isobutyrate (2MIB) are the three primary soluble and survivable hop-derived esters found in hop-forward beers. Together, these esters have fruity apple and apricot-like flavors. Of the three, 2MIB is likely the most dominant component ester. All three of these hop-derived esters have been found to decrease in concentration during wort boiling, suggesting that whirlpooling hops high in these esters is the best way to encourage them to get into the fermenter. Because they are volatile, dry hopping is likely the best method to push hop-derived ester flavors and aromas in packaged beer.

- Isoamyl isobutyrate-rich hops: Ekuanot®, Mosaic®, Simcoe®, Talus™, Idaho 7™, HBC 640, and Sabro™.
- Methyl geranate-rich hops: Centennial (very high), Citra®, Mosaic®, Simcoe®, Chinook, and Idaho 7™.
- 2MIB-rich hops: Idaho 7™ (very high), Ekuanot® (very high), Southern Cross™, Pacific Jade™, Vic Secret™, Bravo, Polaris, Talus™, El Dorado®, and Centennial.

Synergy

It is not just the individual hop-derived compounds described above that give us the flavor and aromas we are looking for in heavily hopped beers; it is also the combination of the compounds working together synergistically to increase the perceptions of flavors. For example, the presence of the hop thiol 3-sulfanyl-4-methylpentan-1-ol (3S4MP) can enhance the perception of the hop ester 2MIB (1). Combining hops like Nelson Sauvin and Southern Cross might help this apricot-leaning ester to shine a bit more. Another example is that the hop thiol 4MMP can have an additive impact on monoterpene alcohols. In other words, when 4MMP from dry hops is introduced to the beer via dry hopping, the perception of compounds like linalool and geraniol can increase even though their concentrations remain the same. Additionally, monoterpene alcohols alone can also work together synergistically to increase the perception of certain flavors. For example, higher geraniol hops (like Bravo) can increase the citrusy and flowery scores of other varieties low in geraniol (Simcoe®).

A 2019 paper found that hop-derived fatty acids play a synergistic role in beer by strongly enhancing the perception and intensity of monoterpene alcohols. Specifically, that paper found the addition of 2-methylbutric acid could enhance the "tropical" characteristic of beer, and isovaleric acid could increase the "fruity" characteristic of beer. Of the hops tested, Apollo and Bravo had the highest concentrations of these two important fatty acids. Slightly aging hops can increase these synergistic acids through oxidative degradation of hop bitter acids into the formation of branched-chain fatty acids.

How Long, What Temperature, and Rousing Methods for Dry Hops

The whole point of dry hopping is to extract the aromatic compounds from the hops, so how long does it take to get peak extraction? Unfortunately, there is not an easy answer. As with everything in brewing, variables matter. For example, what size is the vessel, what hop variety (and product) are you dry hopping with, and how are you agitating the hops in the tank (if at all)?

When it comes to extraction as a function of duration of the dry hop, the science gives a hint into how quickly this can happen. For example, one study found that a week-long dry hop (in a beer-like solution at 1/3 pounds per barrel with no agitation) showed that day 7 concentrations for both linalool (monoterpene alcohol) and myrcene (hydrocarbon) were not higher than day 1 concentrations. Most of the results showed a decrease by day 7 compared with the first day of dry hopping, which suggests that 24 h might be enough to get complete extraction for these two compounds (in a model beer system consisting of 94% acidified filtered water and 6% ethanol).

Another study also found quick extraction from dry hopping, especially with the hydrocarbons, which were extracted in just 4 h. The monoterpene alcohols were also fully extracted in about 4 h, but the shorter extraction time for both classes was likely due to the vessel's constant shaking (more on dry hop agitation below). Even hop-derived polyfunctional thiols can extract relatively quickly in beer, as recent research measured nearly complete extraction of free 4MMP during the first 2 days of post-fermentation dry hopping in centrifuged beer—with little additional extraction between days 2 and 8 (14). So, much like with other hop compounds, extraction during dry hopping happens relatively quickly.

Quick extraction has even been confirmed at temperatures as low as 39°F (4°C), compared with 68°F. Specifically, linalool concentration was measured over 2 weeks at two different temperatures. The authors found peak extraction at day 3 (near maximum extraction on day 2) for both the cold and warm dry hops. The warmer dry hop resulted in slightly less linalool than the cold dry hop (12). Another paper also found that cooler dry hop temperatures had minimal impact on fruity and floral monoterpene extraction compounds (linalool and geraniol) in beer at 33°F (1°C), 39°F (4°C), and 68°F (20°C). However, the warmer temperatures did increase β-pinene, β-myrcene, β-caryophyllene, α-humulene, β-farnesene, 2-undecanone, and 2-tridecanone concentrations significantly (1). I believe that the types of compounds extracted in higher concentrations at warmer temperatures are ones we generally want to minimize in tropical fruit and citrus-forward IPAs (see Table 1).

Similar results were also found with type 90 and type 45 pellets tested at temperatures of 32°F (0°C), 55°F (13°C), and 68°F (20°C) in laboratory-scale trials (1 L Erlenmeyer flasks). Linalool was found to extract well in beer at all temperatures. On the other hand, myrcene was found to extract poorly at cool temperatures but much more efficiently at warmer temperatures (3). I think that myrcene, being a green-tasting and resinous compound at high concentrations, can overtake an IPA by outcompeting the fruiter compounds. Combining the research, we can see that hazy IPAs already retain more myrcene than West Coast IPAs; pairing this with warmer dry hop temperatures will only increase the final myrcene concentration more.

As an aside, I encourage research into how temperature can impact the extraction of hop-derived thiols.

Size matters when it comes to the size of the tank and extraction; the studies mentioned above were done in small beer-like solutions that experienced fast dry hop extraction times. It is likely that the larger the vessel, the slower the extraction, as one expert suggests that it might take 3–5 days to get extraction on a 500 barrel tank and just a day on the homebrew scale (4). Dry hopping is entirely dependent on local diffusion speeds. Anything that speeds up diffusion (stirring, temperature, etc.) will speed up extraction rates, and all those things are generally slower as you scale up tank size. There will be less liquid in direct contact with hop material, and it is harder to move that liquid around.

It is worth pointing out that breweries that don't agitate their dry hops still get great results. I theorize that the time it takes for the dry hops to drift down through the beer to the bottom increases with the tank size and results in better extraction for these larger breweries. On the other hand, dry hops likely reach the cone's base quicker in smaller vessels (resulting in less contact time with the beer and less extraction), especially if dry hopping occurs at cooler temperatures.

Agitation of dry hops can not only help speed up extraction but also increase the total extracted compounds. For example, a study testing hop-derived compounds during a dry hop where the beer was recirculated with a pump found a 58% increase of linalool after just 2 h compared with a control beer that was not recirculated (8). In discussions with other brewers, there are concerns with recirculating dry hops and an increased astringent taste resulting; this is likely because not only are the desired hop compounds extracting at higher rates, but so too are other compounds like polyphenols. Recirculating for shorter durations or using other methods to agitate the hops, such as burping from the bottom of the tank with CO_2, are good alternatives.

Agitation may be even more important for certain varieties of dry hops that have higher levels of alpha-acids. Recent research has found that the higher the alpha-acid concentration in a hop, the fewer compounds were extracted into the beer (1). The study's author suggests that most of the relatively hydrophobic essential oil remains in the relatively hydrophobic alpha-acid phase within the lupulin glands. The higher the acid content, the more of the oil will be held back in the pellets. So, it may be beneficial to perform multiple burps a day with higher alpha-acid hops to encourage a higher extraction efficiency, because static dry hopping would likely result in lower extraction.

Table 1. Odor descriptions of some hop oil hydrocarbons that demonstrate higher extraction at warmer dry hop temperatures (13)

Compound	Odor description
β-Pinene	Resinous, woody
β-Myrcene	Resinous
β-Caryophyllene	Spices, woody
α-Humulene	Balsamic
β-Farnesene	Woody, citrus, sweet
2-Undecanone	Varnish, green
2-Tridecanone	Varnish

Agitation is also likely necessary as the alcohol by volume (ABV) of the beer decreases. The same paper above tested dry hop extraction efficiency at different alcohol concentrations and found the monoterpene alcohols were extracted more efficiently at 5% ABV than in a non-alcoholic beer solution. When the alcohol concentration increased from 5.0 to 8.0%, the hop-derived monoterpene alcohols were extracted at even higher rates, suggesting that as the ABV grows, so does overall dry hop extraction.

In my opinion, if hops are sitting in the bottom of your cone, they likely are not doing you much good in terms of extraction. At Sapwood, we have experimented with multiple methods to agitate our dry hops. We have found that burping from the bottom of the tank has given us some of the best results. However, the specific method of burping has also had significant implications. For example, doing quick bursts of 20–30 PSI while the tank was under pressure did not seem to get the job done. The quick burst method (opening the valve for ~1–2 s) was evident in its lack of agitation after pulling samples immediately after burping and seeing hardly any hops floating in the glass. After extending the duration of the burp to approximately 1 min, we have seen an improvement in hops in suspension and an increase in aromatics. After a burp, you should have a hop salad mess in your glass! Because Sapwood is a relatively new brewery, I reached out to Great Notion brewery to see how their experience on a much bigger scale over the years has influenced their dry hopping and rousing techniques. The key seems to be in scaling the size (duration) of the burp to the overall volume.

Sapwood's Burping Procedure (20 Barrel Fermenters): Columbia, MD

- One to 2 days before dry hopping, drop the tank to 56°F (13°C), harvest the yeast, and drop the remaining yeast.
- Keeping the tank at 56°F (13°C), dry hop with ~4.4 pounds per barrel for most IPAs and DIPAs through the dry hop doser (more on this setup below), and give the hops 4–8 h to saturate in the beer.
- After 4–8 h of dry hop contact time, we burp through the bottom of the cone at 30 PSI for approximately 1 min (purging the burp setup with CO_2 prior to opening the valve to the tank). Generally, the head pressure is around 10 PSI at this point and slowly creeps up to 15 PSI with each consecutive burp.
- Once each day for 3 days, we burp the tank again from the bottom of the tank at 30 PSI for approximately 1 min or until the tank gets back up to 15 PSI.
- After 3 days of dry hopping, we crash the tank 5°F per day and drop hops from the bottom of the cone until reaching 35°F (1.6°C).
- If we are dry hopping in multiple stages, after the first 3 days of dry hopping and burps we will drop the tank to remove as much of the first dose as possible and then repeat our dry hop procedure before moving to the cold-crashing stage.

Great Notion's Burping Procedure (30, 60, and 90 Barrel Fermenters): Portland, OR

- The day before dry hopping, crash the tank to 62°F (16°C) overnight.
- Harvest the yeast needed for future brews, and dump the rest of the yeast from the tank.
- Raise the temperature to 70°F (21°C).
- Using only unopened bags for dry hopping and smelling the hops to ensure quality, add the dry hops through the

dry hop port while running CO_2 into the tank to reduce oxygen pickup.
- Close up the dry hop port and blast CO_2 from the bottom port at 30 PSI for 1 min (purging the valve cup when through the nipple with CO_2 not to force any oxygen trapped in the burping setup into the tank during the burp).
- Blast from the bottom port at 30 PSI for roughly 1 min every day for 6 days, attempting never to blow down the head pressure on the tank.
- After dry hopping, let the beer sit idle for 18–24 h to allow the hops to settle, then do vicinal diketones (VDK) sensory. It can sometimes take a few days to pass VDK.

What Can Go Wrong with a Dry Hop?

Oxygen

Oxygen introduction during dry hopping is one of the enemies of retaining that fresh, bright, and vibrant hop character. Unfortunately, this seems to be especially true for hazy IPAs—more vulnerable to oxidation and coloration than other styles. Interviewing brewers for the *New IPA* book, the most common method to avoid oxidation during the dry hop is by pushing CO_2 through the spray ball after opening up the dry hop port to pour in the hops to create a layer of CO_2 on the surface of the beer (like Great Notion described). While this is better than nothing, I prefer a closed transfer of dry hops into the beer. At least on Sapwood's scale, a 22-pound dry hop doser has been a great addition to keeping our dissolved oxygen numbers down.

A dry hop doser (Fig. 2) mounts to either a 4 or 6 inch valve attached to the dry hop port on the top of your tank. The hop doser is big enough to hold either 11 or 22 pounds of hops and is equipped with hardware to purge the doser and pellets with CO_2 before dropping them into the beer. At Sapwood, we keep the valve to the tank closed, open the dry hop doser from the top, and pour in the hops. After clamping the doser shut, we run CO_2 through the doser for a few minutes (allowing the CO_2 to exit as it enters), then purge it by bringing the doser up to 15 PSI and blowing it down to 0 PSI, and repeat 10 times. After bringing the doser up to the same head pressure as the tank, we can then open the valve attached to the dry hop port, dropping the hops in without opening up the tank. As a bonus, when dry hopping with a hop doser, we do not have to worry about a hop-induced geyser (caused by hops encouraging dissolved CO_2 to come out of the beer).

Figure 2. Dry hop doser. © Scott Janish.

On the bigger scale, other such closed dry hop induction systems exist, usually with the help of a centrifugal or shear pump delivering the hops into your beer attached to a secondary vessel purged and full of hops. Other products like a HopGun® allow a closed system of introducing dry hops to your beer, which you recirculate through the HopGun vessel and back into the source tank to extract the dry hops.

Hop Creep

Dry hopping can produce significant quantities of fermentable sugar in beer due to enzymatic activity from the hops, especially if there is an abundance of dextrins in the wort. This refermentation is now commonly referred to as hop creep. The enzymes most responsible for refermentation are hypothesized to mainly come from amyloglucosidase, combined with low levels of α-amylase and β-amylase activity (6). When these enzymes are active in beer with dextrins available, it can lead to refermentation, especially if yeast is still present. If this refermentation happens after most of the yeast has been removed from the beer, you can produce unwanted off-flavors, such as diacetyl, due to an unhealthy referment. Even if this refermentation is healthy, it can still lead to problems like overcarbonation and packaging issues.

One way to reduce the enzymatic activity from dry hopping is to keep the beer relatively cool. Oregon State University research concluded that shorter (1 or 2 days of contact time) and lower temperature dry hopping at 50°F (10°C), compared with 68°F (20°C), created fewer fermentables. Essentially, there is less chance of hop creep when dry hopping is done cooler and quicker.

There appear to be two schools of thought related to dealing with hop creep. The first is to dry hop warm with extended contact time to encourage any hop creep to happen in the tank, until such time as VDK tests are passed. The other is to do it cool (50–58°F [10–14°C]) and for short duration to try to reduce the overall enzymatic activity that is taking place. At Sapwood, we take the cool and short-duration method and have not had hop creep issues in our cans to date. Other breweries like Great Notion (process described above) take the opposite approach with success.

Increase in pH

One potential problematic impact of heavy dry hopping rates is a rise in final beer pH. Specifically, you can expect around a 0.036 pH increase at a dry hopping rate of ~3 pounds per barrel (7,15). When dry hopping in small amounts, this rise in pH is not likely impacting the sensory beer experience much, but when the dry hop rate is above 3 pounds per barrel (especially when layered with heavy whirlpool additions), the final pH of the beer can get relatively high (4.7–5.0).

It is my experience that when the final pH is at the higher end, it can hinder the drinkability of the beer (and this is especially true in DIPAs). This drinkability issue may be because beer with high final pH values has been tested to taste more bitter than beer with the same iso-alpha content (11). To help set the stage for a lower final pH at Sapwood, we target a low mash pH (5.2–5.3), and we add phosphoric acid to the kettle as we collect to get our post-boil pH in the 4.8–4.9 range.

Although the exact compounds responsible for increasing the pH from dry hopping are not yet known, it is likely due to the hop's leaf material and not from the lupulin glands. Logically, using hop products like Lupomax™ or Cryo Hops® might result in less of a pH increase during dry hopping because so much of the vegetal material has been removed during production.

Increased Bitterness

Although conventional wisdom has always been that you get all of your bitterness from hot-side hop additions, recent research has discovered that is not the case. The hop vegetal material can strip out (adsorb) isomerized alpha-acids, allowing the more water-soluble humulinones (an oxidized form of alpha-acids) to make a more significant contribution to overall bitterness. Dry hopping at a rate of 2 pounds per barrel can reduce isomerized alpha-acids by as much as 38% (10). The loss of hot-side bitterness is replaced to some degree with humulinones during a dry hop, primarily because they are more water-soluble than the isomerized form.

The extraction of humulinones is important because they have been found to be approximately 66% as bitter as an iso-alpha-acids and are described as being smoother in their bitterness profile. In discussions with the paper's author (10), it was said that as a general rule, hopping rates up to 2 pounds per barrel, beer with IBUs under 20 could become more bitter by dry hopping, and beer with starting IBUs above 30 can become less bitter from dry hops. However, when dry hopped at extremely high levels, the increase in humulinones (along with polyphenol extraction to a lesser extent) can increase the bitterness perception. It has been estimated that humulinones have up to 10 times greater influence than polyphenols on dry hop sensory bitterness (16). It should be noted that the standard IBU test cannot differentiate between the different hop acid compounds which have varying levels of sensory bitterness. So, although the IBU test is helpful in a recipe creation and repeatability sense, it is not an accurate figure for true sensory bitterness.

The research on dry hopping and its bitterness implications gives me the confidence to use even more hops in the whirlpool to increase the hop compounds making their way into the fermenter. Despite recipe formulators predicting relatively high (100+) IBU figures for some beers, the adsorption by vegetal hop material reduces the sensory bitterness. I also find, through experience, that the high humulinone concentration from heavy dry hopping does impart sensory bitterness. However, I suppose there is not enough iso-alpha (and with it, other hop-derived flavor active compounds) to pair with the humulinone content arising from dry hopping. In that case, the result can be a vegetal one-note bitterness that is lacking in overall hop saturated flavor and balance. This strong vegetal and tea-like flavor is most likely caused by high levels of dry hop polyphenol and humulinone extraction, which may be enhanced by oxidation because polyphenols can become more black-tea-like when oxidized.

Foam Retention Reduction

A paper that looked at how dry hopping impacts foam retention found that as the pH increased in beer from dry hopping, the head retention also decreased. Cascade hops were used in the paper for dry hopping at dosage rates of 0.5, 1, 1.5, 2, and 2.5 lbs/bbl and were measured for foam stability. As the dosage of Cascade increased, foam stability decreased as the pH increased (20).

Dry hop contact time also had an impact on foam retention; the longer Cascade hops sat in the beer during dry hopping in the study above, the more the foam stability was reduced. This decrease in stability was slight after 2 days of dry hopping, accelerated on day 3, and continued to slowly decrease until day 8. Ultimately, long-term dry hopping can negatively impact foam retention, and this is another reason we limit our dry hop contact time to 3 days at Sapwood.

It also appears that warmer dry hopping may hinder head retention. One study found that the alpha-acids introduced to beer at cool temperatures (tested 57 versus 69°F [14 and 21°C]) are more effective at stabilizing foam retention (20). This could be another factor to help influence colder dry hop temperatures.

Overall, for better foam potential arising from dry hopping, shorter durations (3 days and less) and cooler temperatures (50–58°F [10–14°C]) can positively impact foam.

Polyphenols and Hydrocarbons

One of my biggest complaints with hazy, heavily hopped beers is a green astringent flavor that can dominate the palate and mask the more inviting fruity flavors. This astringency is due to a high amount of hop-derived polyphenols making their way into the beer. Beers that tested high in polyphenols have been correlated to increased bitterness and astringency scores (12).

One way to reduce the overall polyphenol content in dry hopped beers to limit astringency is to limit the contact time and reduce the dry hop temperature. Specifically, it was determined that for dry hopping at 66°F (19°C) compared with 39°F (4°C), there was an increase in polyphenol concentrations of nearly two-fold for a low-alpha hop and almost 2.5-fold for a high-alpha hop. In terms of dry hopping contact time, peak concentrations of polyphenols occurred around day 3 and remained consistent with additional time. Essentially, the extraction of polyphenols is in line with the extraction of other aromatic compounds, so if astringency is a problem, cooler dry hop temperatures are likely the best solution.

In addition to polyphenols extracting at higher rates with warmer dry hop temperatures, other greener and woody tasting hydrocarbons have been tested to also extract at higher rates. For example, testing for the hydrocarbon myrcene at dry hop temperatures of 34, 39, and 68°F (1, 4, and 20°C) it was determined that as the temperature increased, so too did the measured amounts of myrcene (highest levels found in the 68°F [20°C] dry hop) (1). Interestingly, the fruiter monoterpene alcohols tested in the same study were not impacted by the different temperatures as much, likely because of their increased polarity (i.e., higher solubility). Again, I think hydrocarbons like myrcene in excessive concentrations in hoppy beers can hinder the drinkability due to the intense green and resinous character dominating the palate.

Key Findings

Because every brewer's end goal can differ, I think it is best to use a best-practices guide influenced by various studies and experiences to experiment with and improve upon current processes and recipe development rather than completely replace the system in place. Everyone's palates and consumer bases are different, so there isn't a one-size-fits-all solution for dry hopping. Summarizing the material above gives the following:

- The main hop-derived compounds extracted during dry hopping are a combination of hydrocarbons, monoterpene alcohols, polyfunctional thiols, and hop-derived esters.
- Synergy among the classes of hop compounds listed above can enhance the sensory impact without actually increasing the concentration of the compounds themselves (e.g., 4MMP can improve the perception of linalool and geraniol). Diversity in classes of hop compounds can help to increase the complexity of heavily hopped beers.

- The extraction of hop compounds during dry hopping can happen relatively quickly, generally 1–3 days. This is true even at temperatures cooler than fermentation temperatures.
- Agitation of dry hops (i.e., burping or recirculating) can reduce extraction time and improve overall extraction efficiency.
- Minimizing oxygen introduction during dry hopping can go a long way toward maintaining the bright and vibrant hop-derived flavors desired from heavily hopped beers.
- Dry hopping can lead to refermentation, resulting in overcarbonation and off-flavors from "hop creep." Dry hopping at cool temperatures and for short durations can minimize the enzymatic activity responsible for hop creep.
- Dry hopping can increase the final pH of the beer, which can increase the bitterness perception. Experimenting with post-fermentation acid additions to lower the final pH could potentially increase the drinkability of heavily hopped beers. Dry hopping with products with a large portion of the vegetal material removed (like Lupomax™ or Cryo Hops®) could limit the rise in pH from dry hopping.
- Dry hopping can harm foam retention. As with hop creep, shorter dry hop durations and temperatures helped to maintain beer foam.
- Dry hopping at longer durations and warmer temperatures can increase the concentrations of astringent and green-tasting compounds like polyphenols and myrcene.

Recommended Best Practices for Dry Hopping

- Match heavy dry hopping rates with whirlpool hopping at a rate of 1.5–2.5 pounds per barrel at 180°F (82°C) for better bittering balance and increased hop-derived flavor complexity. The reduction in whirlpool temperature helps retain more oil going into the fermenter while also keeping the IBUs down.
- For increased hop-saturated flavor to pair and balance heavy dry hopping rates, consider using hops high in total survivable compounds, (i.e., hop-derived esters, thiols, and oxygen-containing monoterpene alcohols) in the whirlpool, such as Idaho 7™, Mosaic®, Bravo, Citra®, Millennium, Mount Hood, Ekuanot®, and Simcoe®, as well as brewing practices that promote hop oil retention.
- Consider adding additional acid (like phosphoric acid) to the kettle (targeting 4.8–4.9 post-boil pH) when brewing higher alcohol and highly dry hopped DIPAs to counter dry hop pH rise for better drinkability. Post-fermentation acid adjustment to 4.2–4.4 pH can also help.
- Duration of dry hopping for no longer than 3 days, removing spent dry hops from the cone before doing additional dry hop charges.
- Dry hop at cool temperatures, 50–58°F (10–14°C), to improve foam and to reduce excessive hydrocarbon extraction, polyphenols, and hop creep.
- Minimize the oxygen exposure to the beer when dry hoping by purging the dry hops with CO_2 before dropping them into the fermentor. Likewise, adding them to a closed, purged tank, such as with a hop doser, will prevent eruptions and beer showers.
- Agitate dry hops at least once a day to increase extraction efficiency and reduce the extraction time. Consider agitating high alpha-acid hop varieties and low-ABV beers multiple times a day to help with extraction due to the nonpolar nature of hop oils.
- Agitate dry hops with 60 s bursts of ~30 PSI from the bottom of the cone while keeping the tank under 8–15 PSI of pressure.
- Consider dry hopping mid-fermentation to soften or reduce strong resin and/or green-tasting hydrocarbons from hop varieties that have that potential (like Sabro™) that could otherwise dominate the palate.

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