EC3072
January 2024

Hop Cone Drying for the Small Grower: Temperature and Airflow Considerations

Stacy A. Adams, Professor. University of Nebraska-Lincoln, Department of Agronomy and Horticulture
David M. Mabie, Assistant Professor. University of Nebraska-Lincoln, Department of Biological Systems Engineering
Michael F. Kocher, Emeritus Professor. University of Nebraska-Lincoln, Department of Biological Systems Engineering
David Jones, Professor. University of Nebraska-Lincoln, Department of Biological Systems Engineering

Small hop growers without nearby processors for cone stripping and drying must attempt to do so on their own farm. Challenges exist for self-built drying systems, including drying capacity, processing speed, air direction, and maintaining quality during drying. Research-based recommendations are given for optimal temperature, sizing of drying vessel and maximum cone depth, and influences associated with airflow direction on processing uniformity and cone quality are presented.

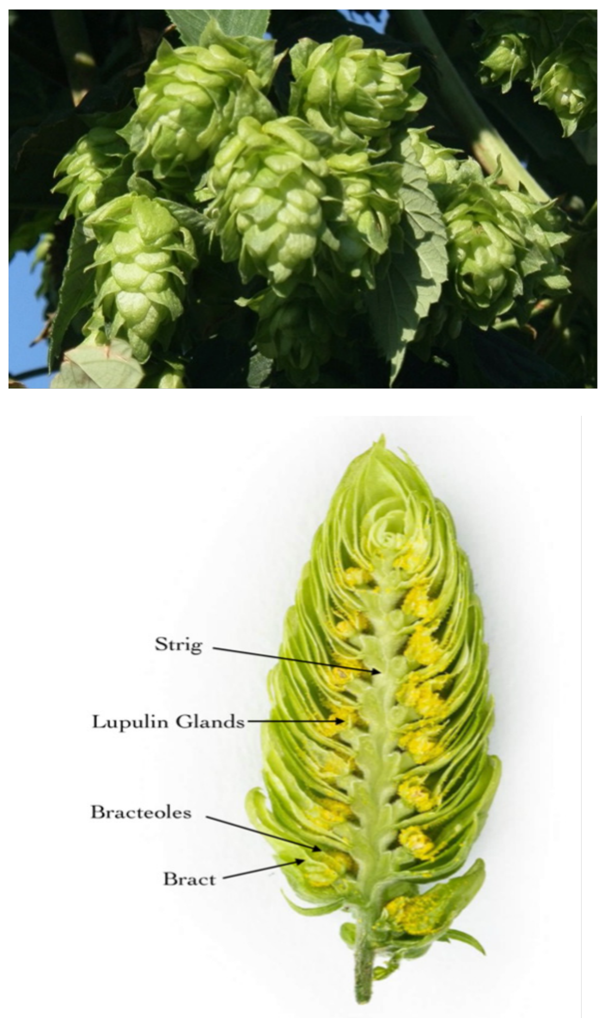
Introduction

For centuries brewers have used hops to contribute bitterness, create aromatic profiles, and for the antimicrobial preservation of beer. Lupulin is the source of these qualities and is the yellow powder visible on the maturing female flowers of hops. The pistillate flower takes on the appearance of a cone but actually is a modified stem-leaf structure that serves as the female flower of this dioecious plant (Figure 1). Lupulin glands form resins, essential oils, and other complex compounds as the flower matures. The timing of the hops harvest occurs when the α-acid, β-acid and essential oils have reached their peak condition. The date harvest occurs can vary among varieties, yearly variation, and environmental conditions. Hops that are picked too early typically have underdeveloped α-acid and the essential oils will consist of more green, grassy, resinous characteristics. Conversely, hops that are picked too late tend to have aromatic profiles that are described as oniony, garlicky, or cheesy. The hop cones increase in moisture content as they approach full ripeness in the fall, with harvest typical when cones reach approximately 75-80% moisture content wet basis.

Figure 1a. Modified stem-leaf structures create the appearance of cones on female hop plants. 1b. Hop cone anatomy (source www.hopfenforschung.de)

a)

b)



It is the grower's goal to capture the best qualities of each hop variety, being the essential oil attributes for bittering, aroma, and flavor, so they have a final product that meets buyers' expectations. Moisture content of the hop cones is checked daily as harvest dates near as essential oil content increases and the complexity of chemical compounds may change. Cones hanging in the field on the bine (a twining stem that wraps a support) dry quickly, typical of the summer heat and dry winds during maturity. Lupulin brewing character can quickly degrade with exposure to light and hot temperatures. Any delay in harvest comes at a cost to hop quality.

Harvesting Cones

Hops historically were handpicked but now most production systems use some type of specialized machines to strip cones from the bines. These stripping machines are often referred to as harvesters and vary in design. Bines are delivered to the harvesters and the base of the bines are attached to a chain driven hook that pulls the entire bine through the harvester (Figure 2). A series of metal fingers spin to detach all the vegetation from the woody bine and the machine's blowers and conveyors sort the cones from leaf litter. Fans are arranged to blow across the conveyed biomass, blowing the lighter stems and leaves from the harvester. The heavier cones may gravity drop from inclining belts or remain on a series of airflow transfer belts until free of debris. Once the cones reach the bottom of the unit, collection conveyors move the cones to a transfer bin or directly to the drying system. Due to the high harvest moisture content at harvest, hop cones must be rapidly dried down to nearly 10% moisture content to properly preserve them for future processing and brewing.

Figure 2. Mature hops are pulled through a harvester to remove all vegetation from the bine and through a series of incline belts and a blower, cones are separated from leaf litter.

Small growers who do not have nearby processors to take their cut hop bines for cone stripping and drying must attempt to do so on their own farms. Challenges exist for the low volume "under an acre" grower desiring to complete the entire post-harvesting process. This includes the speed in which hop bines can be harvested, transferred from the field to the cone stripping unit, the processing time, and limitations related to the method and capacity for drying the cones. Drying is a necessary processing step for most high-moisture agricultural products, and especially the hop cone in which the lupulin is attached. The high moisture content, especially in connection with warm temperatures, encourages volatile compound oxidation, cellular collapse, plant deterioration (rot), and fungal growth that ultimately results in unmarketable product.

Postharvest Drying

Hop cone drying historically was performed in conical kilns called oast houses. These structures contained perforated beds that held shallow layers of cones in which air naturally passed through the cones by convection resulting in slowly drying the hops over a few days. As the use of mechanical harvesting tools increased, so the volume of hops to be processed increased, and growers needed to increase drying capacity to match the harvest rate. Kilns increased drying speed using air heated directly from fireboxes and forced through drying trays using fans. Heat exchangers were later introduced to minimize the contamination from the firebox fuel sources of charcoal or coal. While these batch systems were effective for their time, increased harvest efficiencies demanded innovations in the drying process. A tiered semi-continuous drying system was created to accommodate the increased harvests to allow for hops to being dried immediately after harvest. Fans force air upward through the various tiers of hops layers, with hop cones initially loaded in the highest tier. Periodically each tier of cones is lowered downward nearer to the source of heated airflow. Essentially the driest cones are the bottom tier and the most recently harvested cones would be the top tier. Loading hops into kilns must be completed as uniformly as possible because uneven or under loading results in nonuniform drying.

Air Flow

Hops must have plenty of air passing through the hop drying tray or bed to prevent deterioration of cone quality. It was recommended by Burgess (1964) there should be no more than 6.6 cm depth for each meter per minute of forced air velocity. Burgess developed equations to estimate the minimum time needed to dry hops (Equation 1), however this formula did not consider variation in the depth of loading.

Equation 1. Determination of minimum dry time for hops.

$$MT = \frac{6260}{\frac{VP - vp}{3386.39}\,(3.281a)^{0.39}}$$

Where:

MT = minimum time to dry (minutes)
VP = saturated vapor pressure of water at the drying air temperature (Pa)
vp = vapor pressure of water already in the drying air (Pa)
a = bulk air velocity (mm^3/min . m^2)

This equation can be modified to account for loading depth, in which Burgess referred to as extra time (Equation 2).

Equation 2. Determination of total dry time considering mass of product to dry.

$$T = \frac{1}{\left(\frac{VP - vp}{3386.39}\right)}\left(\frac{2348L}{(3.281a)^{1.047}} + \frac{6260}{(3.281a)^{.039}}\right)$$

Where:

T = total time to dry (minutes)
L = loading of green hops (kg/m^2 of kiln floor)

As demonstrated by these equations, the main conditions that are controllable during the drying process are the bulk airflow velocity, drying temperature, initial air moisture content (by dehumidification) and depth of loading. Bailey (1958) indicated that the experimental equation performs well depending upon the final targeted moisture content. The equations presented provide an initial estimate of the time required to dry hops, which can be verified through intermittent moisture-content testing.

Providing proper air circulation through the hops during drying is necessary to rapidly dry the hops particularly when the beds are filled beyond a single layer of cones. Airflow can be in either an updraft or downdraft direction depending upon the user's preference. Hops creates some airflow resistance related to cone size, shape, and density. Bailey (1958) originally presented the following equation to predict the static pressure drop due to hop airflow resistance from airflow passing through a drying tray (Equation 3).

Equation 3. Determination of static pressure drop from air flow resistance through hops.

$$h_s = \left(0.009589\ \frac{Pa\ \cdot m^3 \cdot min^2}{kg\ air\ \cdot kg\ hops}\right)\rho L v^2$$

Where:

h_s = static pressure (Pa)
ρ = air density (kg/m^3)
L = loading of green hops (kg/m^2 of kiln floor)
V = bulk air velocity (m/min)

Pressure drop data for hops does not exist in ASABE D272.3, *Resistance to Airflow of Grains, Seeds, Other Agricultural Products, and Perforated Metal Sheets Standard 21* (ASABE, 2016). Considerations for maximum airflow velocities must be considered since an excessive air velocity can result in displacing or even fluidizing the hops during the drying process. Bailey (1958) indicated that dry bracts become airborne at velocities exceeding 24 m/min (0.40 m/s) and dried whole cones become airborne at velocities above 46 m/min (0.77 m/s). Current guidelines suggest an upper limit of air velocity of 0.30 m/s within the hop bed (Neve, 2012) which should prevent the blowing of cones from the drying bed.

Air Flow Temperature

The air temperature to which hops are exposed has a significant effect on the maximum drying rate of hops. In the previous equations the saturation vapor pressure is determined at the ambient air temperature and elevates with increasing drying air temperatures. Temperature of the drying air has an impact on color, appearance, storability, and qualitative characteristics of hops. Burgess (1964) showed that the quantity of alpha acids in hops cones decreased as drying temperatures increased, thereby reducing the market value of each batch. In addition, it was concluded that the market value of hops as judged by appearance, rub, aroma (essential oils), and the preservative value decreased as drying temperature increases.

Some growers have explored an alternative approach to drying hop cones using dehumidified air rather than heating air. The system described by Peacock (2018) shows a downdraft system that allows for intermittent loading. The downdraft system allows hops to dry from the top layer of hops down. More lupulin is retained on the cones and visible attributes expressed by cone quality are maintained when lower air temperatures are used during drying. While the dehumidified system showed improvements in consistency of cone drying throughout system, the time to dry is considerably longer than using heated air thereby decreasing the total processing rate of hops from field to baling or final processing.

Essential Oil

Hops are the key ingredient for brewing beer, specifically for adding bittering and the addition of unique flavor and aroma characteristics. Essential oils are complex, containing many classes of chemical compounds that include both volatile and non-volatile fractions (Dietz et al, 2020). The α- and β-acids characteristics of hops are the primary consideration when referring to bittering hops and primarily used at the beginning of the wort boiling stage. Aromatic hops are those added to impart aroma profiles from the essential oils and to a lesser extent, flavor. Essential oils are typically extracted for analysis through steam distillation, therefore, when hops are added during the wort boiling phase it is likely that the essential oils are inevitably mostly volatilized. This means that the addition of cones at varying times during the boiling will generally affect the overall aromatic profile the brewer wishes to impart. In addition, some brewers introduce hops at the end of the brewing process during a time when no heat is given (flameout) to increase aromatic qualities, commonly referred to as dry hopping.

Considering the various qualities brewers wish to control in the art of craft brewing, maintaining hop quality and the complex volatile compounds are of utmost importance. Growing hops is only one aspect of creating quality cones since postharvest handling and the process of drying hops greatly influences final product character. Growers need to consider carefully the cone drying process that produces a consistent product within the entire product lot. The drying vessel dimensions, uniformity of drying air moving through the vessel, ability of the drying air to carry the moisture from the cones, and changes to cone structure during drying, including whether heat is used or not, are all important considerations in the design of the drying system.

Cone Drying Research

Hop cone drying research was conducted by Biological Systems Engineers at the University of Nebraska-Lincoln from 2018 through 2020. The purpose of this work was to explore air flow uniformity related to shape of drying bed (vessel), consistency of airflow resistance by direction of airflow, and temperature effects on dry time and content of essential oils. This information would be useful to small growers for designing their own hop drying system.

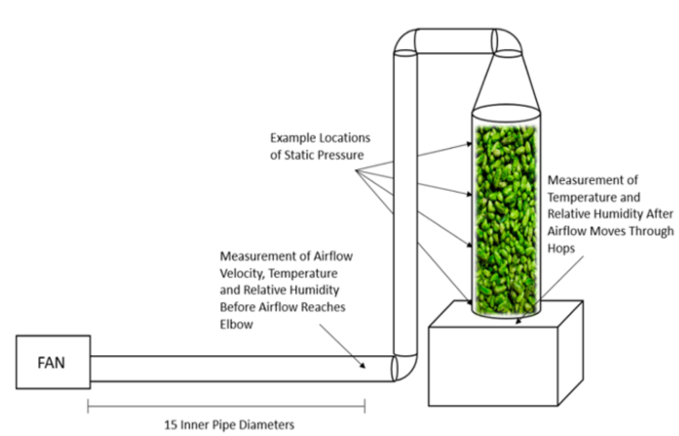
Shape of Drying Bed

A comparison was made for airflow resistance in relation to the shape of the hop cone drying bed. Two columns were constructed each one meter in height. The first was a round column with a 0.3 m internal diameter and the second was a square column of 0.3 m by 0.3 m. Airflow from a fan was directed upwards through the bottom of each of these columns containing a 0.9 m depth of cones. The air pressure throughout each of the columns was determined experimentally. It was determined that the circular bed geometry had more airflow resistance than the square column. This difference indicated a more uniform passage of air through the entire round column. There were significant differences of pressure drop per depth among the different varieties in this study, generally related to cone size and shape, but it is unlikely to have a large impact on fan selection. It was noted that natural variation occurring as the hop cones dry would likely impact the overall airflow resistance much more than the observed differences for bed shape and variety.

Airflow Direction

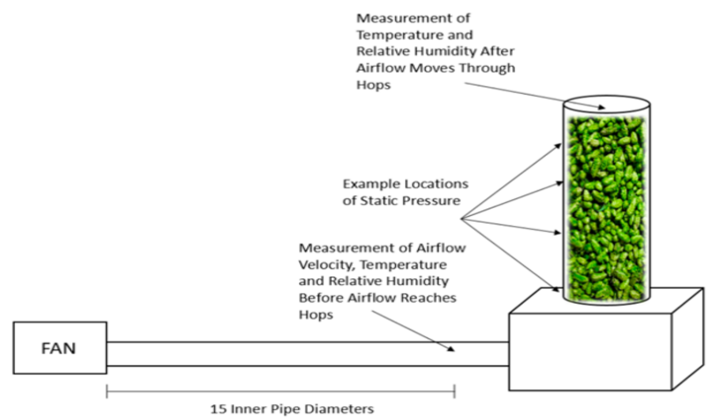
Comparisons were made to determine the impact of direction of the airflow moving through the drying bed, either blowing downward (Figure 3) from the top of the column (downdraft) or blowing upward (Figure 4) from the bottom of the column (updraft). A clear difference in airflow resistance was observed, with the downdraft airflow direction having the higher airflow resistance (Figure 5). The downdraft airflow is likely increasing the airflow resistance by compacting the hops, while the updraft airflow is fluidizing, or fluffing the hops, reducing the overall airflow resistance. As the hops dry, it would be expected that the overall airflow resistance would decrease. Depending upon the airflow per bed area in the drying system design, the user might require

Figure 3. Downdraft configuration to study static pressure within a round drying column.



some means of reducing the airflow rate to avoid the creation of blowholes (downdraft airflow direction) or blowouts (updraft airflow direction).

Figure 4. Updraft configuration to study static pressure within a round drying column



Dry Time

The hop varieties were dried at four different temperatures, of 22.5 °C (or normal ambient air temperature), 37.8 °C, 48.9 °C, and 60.0 °C. The rate of drying was varied between hop varieties due to structural aspects of the cone, the exposed surface area, and tendency for the cone bracts to open and "feather". Feathering could lead to bract leaves separating from the cone and increased likelihood of blowing out of the drying vessel. Multi-stage drying could be considered to dry each part (bracts, bracteoles, and strig) of the hop cones using different control settings (airflow rate through the bed, drying air temperature, air humidity). If the cone is dried too rapidly, the structural integrity of the cone can begin to fail and lead to significant loss of lupulin in the final product. Modifying the drying rate through changes to drying air temperatures, airflow rates, or air humidity at each stage of the drying process could minimize losses to the physical integrity of the hop cone.

Temperature Effects on Essential Oils

Three hop varieties were compared for essential oil content in relationship to the four different drying temperatures used to explore dry time. Results indicated significant differences in the total essential oils content between the maximum and minimum hop drying temperatures for all three 2020 hop varieties studied (Table 1). When plotted, these results illustrate a negative linear regression for each of the varieties (Figure 6). These results, as well as findings from the 2019 essential oils analysis, illustrates that the total essential oil content decreases as the hop drying temperature increases. These results are consistent with previous research done by Burgess (1964) for alpha and beta acid content.

Figure 5. Comparison of Updraft and Downdraft airflow direction measured at midpoint in column.

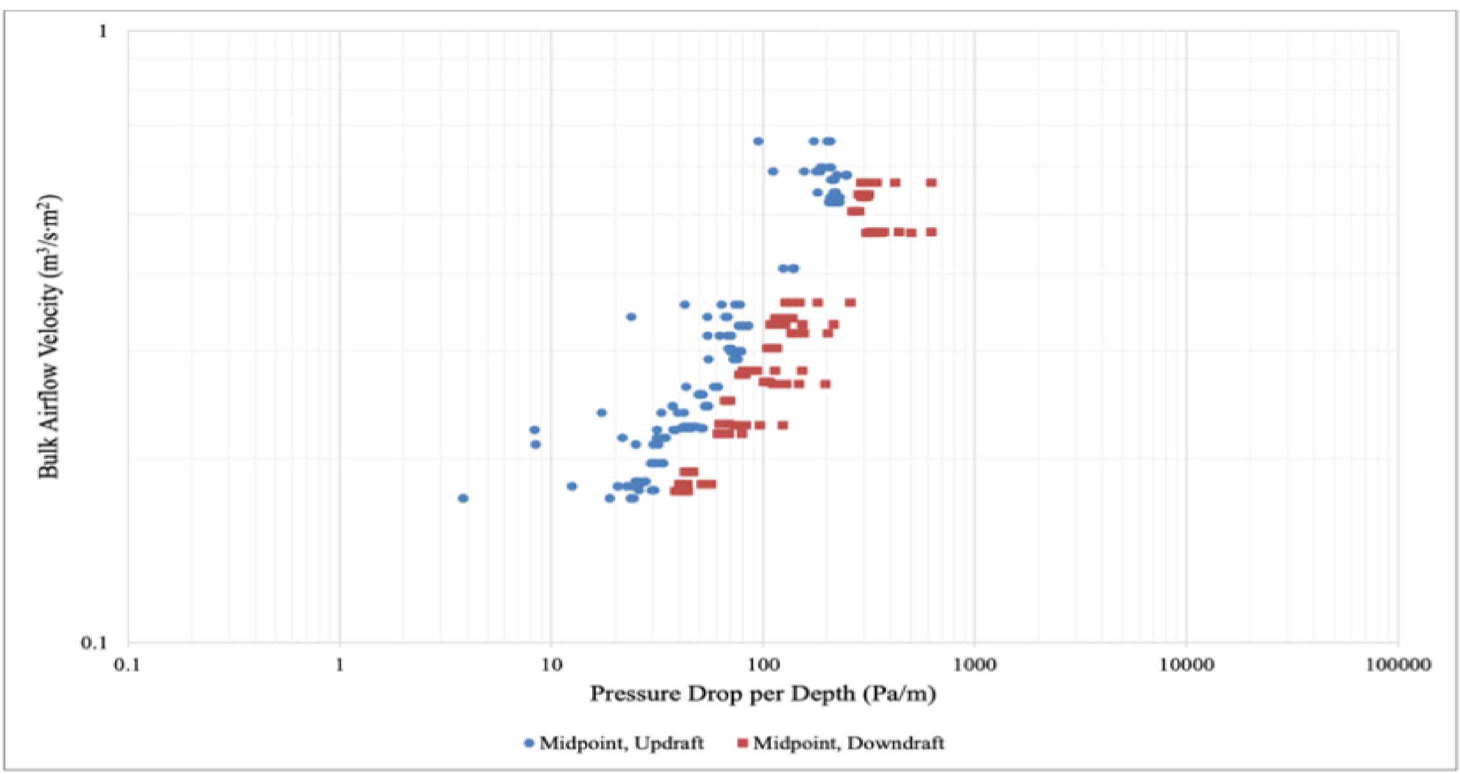


Table 1. Total essential oil concentration for three varieties dried at 22.5, 37.8. 48.9 and 60o C for the 2020 trial.

Hop Variety	Drying Temp (°C)	Total Essential Oils (mL/100 g Dry Matter)
Chinook	22.5	1.94 ± 0.09
Chinook	37.8	1.82 ± 0.12
Chinook	48.9	1.78 ± 0.09
Chinook	60	1.67 ± 0.24
Tahoma	22.5	1.98 ± 0.07
Tahoma	37.8	1.83 ± 0.07
Tahoma	48.9	1.81 ± 0.09
Tahoma	60	1.73 ± 0.04
Triple Pearl	22.5	2.06 ± 0.23
Triple Pearl	37.8	2.01 ± 0.11
Triple Pearl	48.9	1.87 ± 0.16
Triple Pearl	60	1.82 ± 0.11

Recommendations

Small capacity hop growers who desire to strip mature cones and dry them from ~77% to ~10% moisture content must consider their ability to complete these actions in as timely manner as possible. Harvest delays affect essential oil character and visible quality of the cone. Depending upon the quantity of hops to be dried, decisions need to be made on the speed at which postharvest drying must be completed. Drying system airflow is critical for cone tissue moisture to be transferred out of the drying container and away from the cone. Cones in the drying container must be uniformly dried with minimal amount of lupulin loss and deterioration of desired qualities. Parameters to consider include the bed geometry, depth of cones in the bed, direction of airflow, supply air temperature, and the rate of airflow.

Data obtained from the airflow resistance analysis enabled determination of appropriate a and b airflow resistance coefficients (Table 2) associated with the formula (Equation 4) used to determine the size of fans necessary for drying hops. This information was previously lacking specific to hops airflow resistance in ASABE D272.3, *Resistance to Airflow of Grains, Seeds, Other Agricultural Products, and Perforated Metal Sheets Standard 21* (ASABE, 2016).

These coefficients could be used for either heated or dehumidified drying air allowing further applications of the constants.

Equation 4. Airflow resistance equation to provide guidance for drying fan size.

$$\frac{\Delta P}{L} = \frac{aQ^2}{In(1+bQ)}$$

Where;

ΔP = pressure drop (Pa or inches of water)
L = bed depth (m or ft)
a = constant for a particular material
Q = airflow $\left(\frac{m^3}{s \cdot m^2} \; or \; \frac{ft^3}{\min \cdot ft^2}\right)$
b = constant for particular material

Figure 6. Comparison of Total Essential Oil content in relationship to increase of drying temperatures and cone variety.

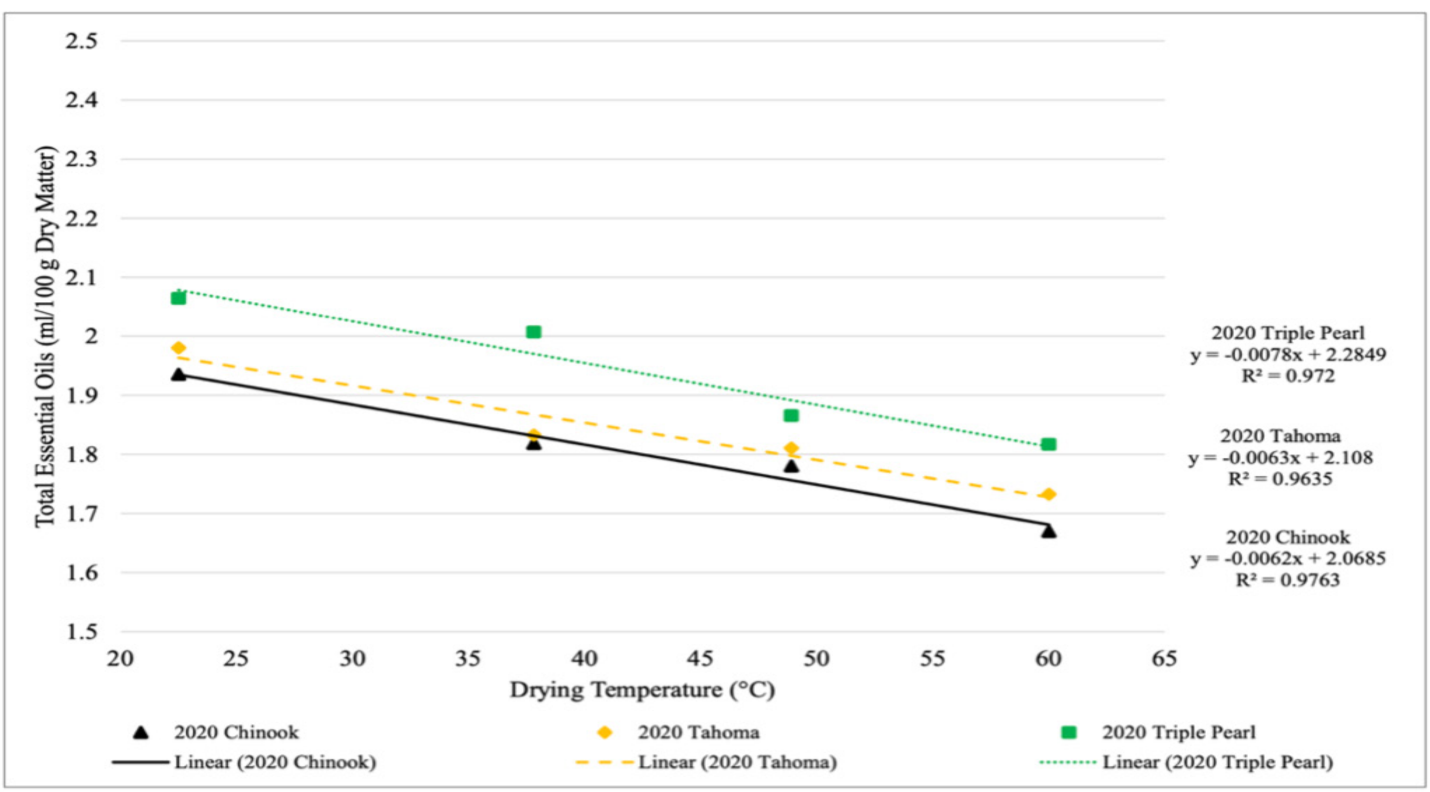


Table 2. A and b coefficients for different hops varieties in both updraft and downdraft airflow directions.

Airflow Direction	Variety	a $\left(\frac{Pa\,s^2}{m^3}\right)$	b $\left(\frac{s}{m}\right)$
Updraft	All	1,980	30.7
Downdraft	Chinook	13,900	288
Downdraft	Tahoma	23,200	2,690
Downdraft	Triple Pearl	7,310	288

Research indicated that a round drying bed, compared to a square bed, maintained more consistency in air resistance throughout the hops being dried. This difference was negligible to that in uniformity of loading cones in the drying bed and the changes that naturally occur as the cones dry. Airflow during drying can be accomplished in either a downdraft or updraft configuration, however, downdraft exhibits more uniform resistance throughout the bed that prevents cone fluffing and lofting and demonstrated more consistency through the bed depth when the fan was properly sized.

In considering the air temperature used to dry hops, the grower will need to balance the drying time needed against the potential loss of resins and essential oils. While literature and this research indicates there are losses in the total essential oil content as drying air temperature is increased, the significant addition of time required to dry hops with lower air temperatures may have a greater negative impact if it results in the inability to fully dry the crop. Further application on the assessment of the rate of drying could allow the grower to consider multi-stage drying systems to dry portions of the crop at different drying rates to produce a more desirable hop. While many of these decisions require weighing of multiple factors, the grower should always work with the brewer to ensure their product meets the needs of the consumer.

Additional Hop Publications from Nebraska Extension:

Adams, S.A. (2018). Hops on a Quarter-Acre. Nebraska Extension. EC3026.

Adams, S.A. (2021). Cultivating Hops for Cone Production in Nebraska. Nebraska Extension. EC3050.

Acknowledgements:

Research was conducted in partial fulfillment of requirements for the degree of Doctor of Philosophy for David M. Mabie. Presented to the faculty of the graduate College at the University of Nebraska-Lincoln. August 2021

This work was supported in part from the Nebraska Specialty Crop Block Granting program, Development of Optimal Hop Drying Techniques for Nebraska

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Bailey, P.H. (1958). Hop drying investigations. Part III: Some properties of hops relating to the drying process. *J. agric. Engng Res.*, 3(3), 226-234.

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Dietz, C., Cook, D., Huismann, M., Wilson, C., and Ford, R. (2020). The multisensory perception of hop essential oil: a review. *J. of the Institute of Brewing*, 126(4), 320 – 342.

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