Crop Management Strategies for Hop Production in Alabama

by

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A thesis submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Master of Science

Auburn, Alabama
December 13, 2025

Keywords: mulching, hops cultivar, trellis system, hop yield, cone quality

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Abstract

This thesis investigates the impact of crop management strategies for hops, including mulching, trellis system type, and cultivar selection in Alabama. This study aims to evaluate the relationship between these treatments and the performance of hop plants (i.e., growth, photosynthetic response, yield, cone size, and cone quality). Findings reveal a significant influence of cultivar, mulching, and year-to-year variability with yield, as well as cone quality. Cone yield decreases significantly when stress increases, especially during the developmental stage of cones. The use of V-trellis systems did not significantly differ than the use of straight trellis systems in this experiment. These results suggest that cultivar selection is crucial for Alabama hop production, and trellis type may not improve yield or performance during the initial years of hop establishment and/or in under instances of stress.

Artificial Intelligence (AI) Use Disclosure Statement

In the preparation of this thesis, the following Artificial Intelligence (AI) tool was used: Microsoft 365 Copilot. This tool was used primarily to assist in generating, editing, and/or refining lines of code for RStudio during statistical analysis and figure creation. It was also used to improve flow, formality, and writing errors. The author acknowledges full responsibility for the intellectual content of this work and has ensured that all AI-assisted sections have been reviewed and revised for accuracy and appropriate academic style. All AI-generated content was reviewed and validated for relevance, appropriateness, and accuracy before incorporation into the final document to maintain scholarly integrity of this research.

Acknowledgments

The completion of this experiment and its findings could not be accomplished without the collaboration of many individuals. I would first like to thank my advisor, Dr. Andre da Silva, for granting me the opportunity to become a researcher, especially on such an exciting and refreshing topic. Your accommodations, understanding, and sense of humor helped me on a personal and professional level. I would also like to thank all my colleagues for their generous assistance in field tasks, harvesting, and analyzing, especially Michell Goncalves De Oliveira, Dr. Victor Hugo Cruz, Dr. Jessica dos Santos Pizzo, and Dr. Fatima Zahra Rezzouk. Your continual selflessness, encouragement, knowledge, and friendship allowed me to produce work that we can all be proud of. Thank you to Dr. Ann Ojeda for opening your laboratory to us, for your expertise, and for your infectious excitement. Thank you to all the collaborators at the Ornamental Horticulture Research Center in Mobile, Alabama, especially Kyle Owesly, Jeremy Pickens, and Alysa Gauci. Through the challenges that came with this experiment, you persevered and helped carry it to the end. Thank you to my dear family, especially my sibling and fellow researcher, Veronica Lahue, for your support, advice, and laughter throughout this entire process. I look forward to seeing your future work and publications. To Sunny Eliza Waller, my good friend, I wouldn't be the person I am today without you, and you live on in my work. Finally, to my husband, Race Bottcher, you might as well be a researcher yourself. Thank you for all your hard work in the field and otherwise. You were there for me during the long nights, uncertainty, and unexpected events of poor health. You did it all without expecting or wanting anything in return. You believed in me when I didn't believe in myself, and I am forever grateful for you.

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List of Abbreviations

A	Photosynthesis rate
ADH	*n*- + Adhumulone
ADL	*n*- + Adlupulone
CAS	Cascade
CHI	Chinook
Chl	Chlorophyll index
COH	Cohumulone
COL	Colupulone
Cu	Cultivar
DBY	Dry biomass yield
DCY	Dry cone yield
ETR	Electron transport rate
FBY	Fresh biomass yield
FCY	Fresh cone yield
gs	Stomatal conductance
HPLC	High-performance liquid chromatography
LAI	Leaf area index
MAG	Magnum
NEO	Neo1
NUG	Nugget
Tr	Trellis
Yr	Year

Chapter 1: Literature Review

1.1 Introduction

A key ingredient in the production of most beers is hops (*Humulus lupulus*). The demand for locally sourced hops has increased with the establishment of Alabama’s microbrew industry. Despite demand, hops are not a crop produced in the deep south, but in northern latitudes. The primary reason behind northern production is photoperiod and milder growing conditions.

Because hop production has been limited to northern parts of the United States, little is known about cultivar selection, disease and insect presence, and yield performance related to Alabama’s climate. Furthermore, it is imperative to understand *H. lupulus* as a cultivated crop prior to experimentation and discussion, including its characteristics, origin and domestication, management practices and challenges, and significance to people and the economy.

1.2 Botanical Description, Origin, and Domestication

Hop is a crop in the Cannabaceae family grown for its strobili, or more commonly referred to as cones. *H. lupulus* is one of the three major species of hop plants found in the world, the other two being *H. japonicus*, native to China and Japan, and *H. yunnanensis*, in which there is very little cultivation. Additionally, there is a form of wild hops found in the western part of North America, called *H. lupulus* var. *neomexicanus* (Neve, 1991).

The *H. lupulus* will be the focus of this research. It is a dioecious perennial climbing plant with twining bines and hooked hairs. Hops can be identified by lobed leaves with toothed margins in pairs or even in threes at each node. Further, following pollination, bracteoles become enlarged and form strobili (Neve, 1991; Miller, 1957). Within strobili, there are lupulin glands full of resins. Hop resins contain most notably α-acids and β-acids, as well as essential oils. The α-acids within the cones are an important aspect of beer brewing as they are the source of bitterness, while the oils and β-acids add a variety of flavors and aromas (Bocquet et al., 2018; Pistelli et al., 2018).

Hop plants are propagated from their lateral underground roots, or rhizomes, after dying back in the winter. The upper part of the "crown" is what can produce new buds and shoots in the spring. According to Neve (1991), hop plants are typically not propagated from seeds, as the progeny are extremely variable and therefore often have little commercial value.

A major consideration when concerned with genetic variability is photoperiod responses and uniformity within the crop. The photoperiodic response of hops can vary depending on the earliness of flower for the cultivar (Roberts et al., 1980).

Hops are long-day plants and typically require 15.5-16.5 hours of light per day, or more in cooler temperatures, to induce flowering (Thomas and Schwabe, 1969). Increasing daylength beyond this photoperiod results in delayed flower initiation, but more abundant flowering overall. Maximum cone production has been shown to improve with daylengths slightly shorter than the aforementioned critical requirement. Contrarily, when daylength is less than the minimum required, growth can be stunted due to early floral initiation (Neve, 1991).

1.3 Historical and Economic Significance

Hops are primarily grown for beer production; however, they have had many uses historically. These include being eaten in salads, ground into flour for bread making, and woven into fiber cloth and paper. Hops were even thought to relieve physical health ailments, such as pain from birth, tumors, and blood impurities. It is believed that hops were originally added to beer to keep them from spoiling, as they contain antibacterial properties, and it was only later that their flavor and aroma became noticed and favorable (Neve, 1991; Hieronymus, 2012).

Nowadays, the use of hops goes beyond alcoholic beverages as shoots are a great fat-free and high protein, high fiber food source, making the leftover plant material from cone production desirable in the culinary industry (Rossini et al., 2020). In the pharmaceutical industry, modern research suggests that the flavonoid xanthohumol derived from hops contains cancer-fighting properties. Particularly, they are being used to treat excitability, mood disturbances, and sleep disturbances due to their sedative quality (Hieronymus, 2012). A recent study at Korea University in Seoul supports this use by showing that extracts from *H. lupulus* improved sleep-related behaviors, including sleep duration (Min et al., 2023).

In general, hops are primarily grown for their cones, and therefore their value lies within the harvesting and yield of strobili. The United States is the number one grower, producing 50% of the world's hops in 2022, followed by Germany, producing 32%. Other contributors include the Czech Republic, China, and Poland (BarthHaas Report, 2024). Within the United States, the top producers have consistently been the states of Idaho, Oregon, and Washing (USDA, 2023). Their output accounts for nearly 98% of all hops produced in the U.S. (USDA, 2023). According to the USDA National Hop Report (2021), hop production increased by 11% in 2021 from the previous year. In 2023, hop production increased 2% from the previous year. This shows a rise in demand for the crop in recent years (USDA, 2023). As the demand for hops increases, the need for expansion, and therefore research, into other regions also increases.

However, 18,127 hectares (44,793 acres) of hops of hops were harvested in the United States in 2024, which is 18% lower than the previous year (USDA, 2024). While hop yield was 29 pounds more in 2024 (1,944 pounds per acre), the value of hop production was $466 million, which was 21% lower than the previous year (USDA, 2024). This could be due to a higher demand for less “hoppy” beers as well as economic challenges, particularly “rising production costs caused by inflation in energy, material, and labor costs” that make it difficult to sell hops at a low market price (BarthHaas, 2025).

1.4 Cultivar Selection

Cultivars should be properly selected before planting and selection is based on several factors. Region and climate, site, yield potential, cone size, growth rates and desired harvest dates, desired aroma profiles, bitterness, and/or oil content of cones (and consequently, one’s market) should all be considered when choosing a cultivar (Alas, 2022).

Current studies indicate ‘Cascade’ and ‘Chinook’ to have a high adaptability for more tropical climates (high heat and humidity), as demonstrated in an experiment that compared three American cultivars and a European cultivar in Brazil (Contin et. al., 2023). Similarly, a study in Brazil under subtropical conditions tested the cultivars ‘Comet’, ‘Chinook’, ‘Cascade’, ‘Nugget’, and ‘Columbus’. All cultivars performed well photosynthetically, with ‘Comet’ and ‘Nugget’ having the highest yields and ‘Cascade’ with the best productivity (Neves et al., 2024). In the Southeastern U.S., ‘Cascade’ has been used in Florida, but no report has been found in Alabama other than initial trials conducted at the E.V. Smith Research and Extension Center from Auburn University in Shorter, Alabama (da Silva and Danderson, 2022).

A study evaluating cultivar under different temperature treatments found that ‘Cascade’, ‘Willamette’, and ‘Southern Brewer’ are stable cultivars for warm climates and could be used for breeding programs to “improve abiotic stress tolerance” (Eriksen et al., 2020). While ‘Chinook’ seems to generally perform well in tropical and subtropical environments, this study found that it may be more susceptible to extreme heat stress. Overall, results from this experiment showed that hops perform best at temperatures from 21 to 39°C (about 70 to 102°F), and regions that experience temperatures higher than this for prolonged periods of time may see a decrease in productivity for their hops (Eriksen et al., 2020).

1.5 Production Methods

1.5.1 Hopyard Establishment

Hops are a perennial multi-year crop. In years one and two, cone quality and yield gradually increase each year with peak performance beginning in year three when crops are established (Brooks et al., 1961). Hagemann et al. (2024) observed an increase in α-acids and β-acids in the initial three years of a hopyard establishment. Therefore, it may take up to three years before a hopyard becomes the most profitable, and analyzing hops in their first-year growth period can help assess the potential of commercial production for a given cultivar, as well as provide insight on strobile production across cultivars (Pearson and Smith, 2018).

Hops perform best in deep, loamy fertile soil without the risk of flooding. Despite a high water demand, hops do not perform well under excessive moisture. In Georgia, preferred planting sights include south sides of a gentle slopes due to high light interception from the sun and minimized damages from wind (Tomlan, 1992). The importance of location was illustrated by Hagemann et al. (2024) where cones were harvested with different characteristics (hilltop vs shallow valley). Plants grown in the shallow valley benefited from a greater degree of protection and thus produced quality cones with more α- and β-acid content. Additionally, Rodolfi et al. (2019) found that plants of the cultivar ‘Cascade’ grown under similar conditions in Oregon and Michigan produced different yields and quality of cones. In Oregon, α-acid content was higher and had an overall higher oil yield, while in Michigan, β-acid content was higher but with a lower oil yield. In conclusion, authors stated that the environment in which hops are grown must be considered, and some variability can be expected depending on specific climates. More specifically, differences in temperature, rainfall, and soil composition can “influence the DNA methylation process, turning on or off specific genes, so that although DNA is the same, the methylation model changes” (Rodolfi et al, 2019).

Testing and correcting the soil for a hopyard is crucial and should be conducted before the hop season begins in the spring. This helps determine the soil type, soil pH, nutritional needs, and the presence of nematodes. Following testing, soil amendments can be made, such as adding lime and fertilizers according to soil test recommendations (Agehara et al., 2020).

Trellis construction is another vital step in preparing a hopyard. The trellis system must ensure maximum longevity of the crop (10 – 15 years). Short-trellis systems are 3 m tall, while typical trellis systems are at least 4.5 m, but they can be 5.5-6 m tall (Dodds, 2017). While utilizing short trellises reduces the labor, installation, and specialized equipment costs, production is limited as plants are unable to reach their maximum height. Yields from short trellis systems have been shown to be drastically reduced, anywhere from 26 to 80% compared to taller systems (Darby, 2004). Similarly, Ježek and Matthews (2019) also demonstrate an overall higher percent of cones despite having a lower percent of bines in tall trellises compared to low trellises across two cultivars, ‘Premiant’ and ‘Sládek’. For the low trellis plants, the ratio of bines to cones within total biomass were 38:13 for ‘Premiant’ and 25:24 for ‘Sládek’. In contrast, on the tall trellis, ratios of bines to cones were 19:36 for ‘Premiant’ and 18:36 for ‘Sládek’ (Ježek and Matthews, 2019).

Commercial growers utilize one of two trellis systems: straight trellis and V-trellis. Figure 1.1 shows the difference in these two setups. Straight trellises require only one cable spanning over each row of hop plants. V-trellises can have a cable on each side of the row, as well as support cables spanning horizontally, requiring up to 370% more cables than the straight trellis design. Because of the additional supplies required, V-trellises are more expensive, with the straight trellis setup costing $5,573 USD and the V-trellis setup costing $8,225 USD per acre (Agehara et al., 2020).

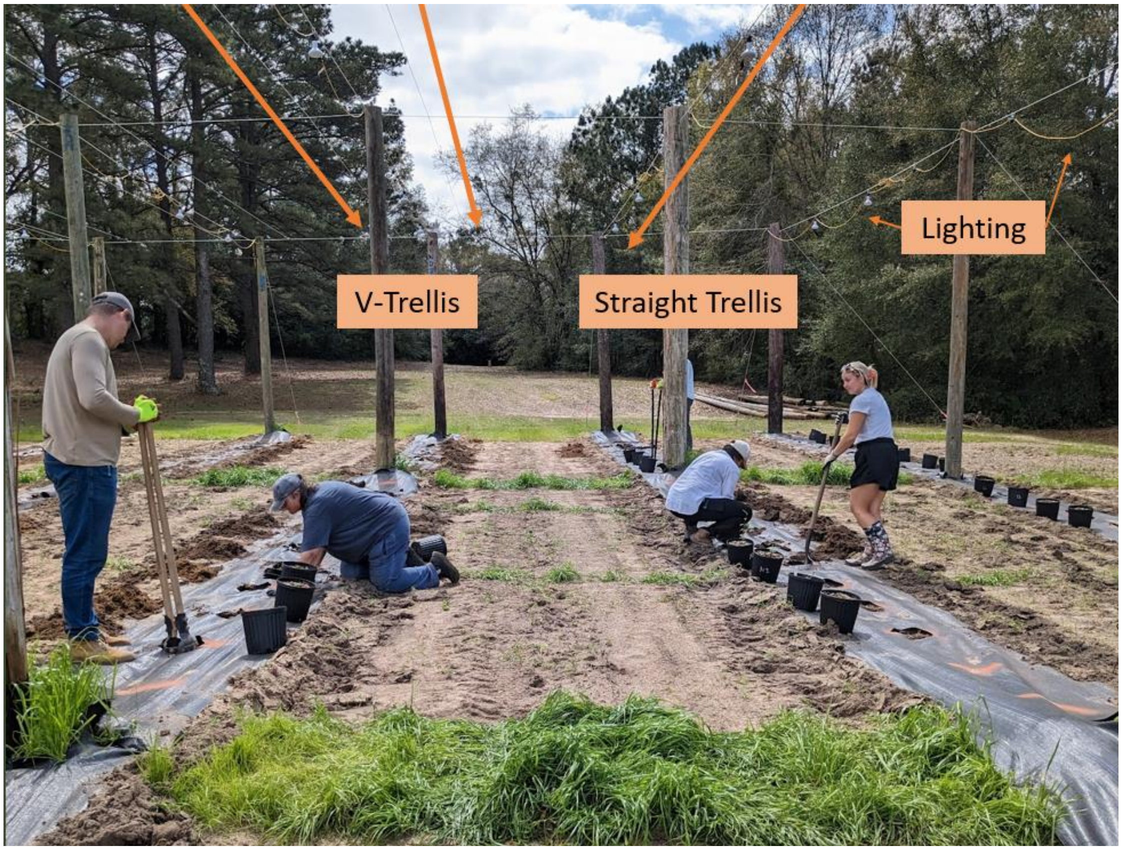

Figure 1.1. Straight trellis and V-trellis designs.

1.5.2 Crop Management

Hops can be planted directly in the field using either dormant rhizomes or containerized transplants. Rhizomes are a popular choice among growers as they do not require as much care as a containerized plant, can be planted in the late winter or early spring, and are less expensive. Shoots from the rhizomes will later emerge in the spring post-frost. Containerized plants must be planted after the last frost date in the spring. If they are planted in the fall, they must be placed at least six weeks before the first frost date (McWhirt et al., 2021). Plants are commonly spaced 60 – 150 cm (2 – 5 ft) apart, depending on the trellis design and cultivars selected (McWhirt et al., 2021).

One of the challenges for growing hops in Alabama is the short daylength cycle of about 14 hours or less during the peak growing season, resulting in early flowering and reduced yields. This is below the required daylength of about 15 – 17 hours (depending on cultivar and climate) (Thomas and Schwabe, 1969). Supplemental lighting can be provided to delay flowering, allowing the plant to accumulate the necessary amount of biomass for the greatest yield potential. Use of artificial lighting has been shown to increase vegetative growth, providing adequate biomass accumulation before flowering, for maximized cone yield (Leles et al., 2023). Deep red/white LEDs are recommended to extend day length, especially in long intervals after dusk or before dawn, as opposed to shorter night-break lighting (Agehara et al., 2020; Meng and Kelly, 2024). Additionally, the use of red and far-red lighting can be generally more effective than broad-spectrum warm-white LEDs (Meng and Kelly, 2024). An initially cheaper option of halogen bulbs may also be used, although they are less efficient and generate a substantial amount of heat (Leles et al., 2023). Spacing bulbs at 6 meters (20 feet) apart is sufficient, while supplemental lighting can be used for up to six hours in the night in Southeastern U.S. regions to extend day length to more than 17 hours (Agehara et al., 2020).

As aforementioned, hops require plenty of water but can be affected by standing or excess water, so effective irrigation management is important. Rhizomes are sensitive to rot after 48 hours of flooding, impacting plant growth and biomass accumulation in future seasons (Greer et al., 2018). The amount and frequency of water provided to the hops depends on trellis system, the type of soil, and environmental conditions (Dodds, 2017). For example, a sandy loamy soil may require more irrigation than higher organic matter soils with clay content. Regions with higher temperatures may also require more irrigation.

Fertilization requirements vary depending on the age of the hopyard, soil test results, cultivar in use, and the growing region (Rossini, 2021). Hops in their first year, for example, require less fertilization than hops in their third year once they reach their full yield potential. Nitrogen application is very important for sufficient vegetative growth before flowering, and nitrogen fertilizer rates can vary from 85 to 170 – 220 kg per hectare (75 to 150 – 200 lbs per acre). Lower rates are often applied in the first year and can be increased with each year and its rising yield potential. Applying more than what is necessary in the first growing year will not improve yields (Tackle and Cochran, 2017). Particularly, there is a correlation between biomass accumulation and total nitrogen uptake, indicating the rapid use of this nutrient during the vegetative growth stage (Gingrich et al., 1994). However, when nitrogen is applied late or after the vegetative growth stage, it can cause an accumulation of nitrogen in the cones, affecting acid and oil content and overall quality of the strobili (Iskra, 2019). Potassium is also an important nutrient for bine growth and cone development and is applied before planting at a rate of 90 – 170 kg ha^{-1} (80 – 150 lbs $acre^{-1}$), depending on soil test results (Dodds, 2017). Phosphorus is the least demanding nutrient for hops and is usually only applied when soil levels are very low at a rate of 22 – 34 kg ha^{-1} (20 – 30 lbs $acre^{-1}$) during site establishment.

Once the hops have been established and grown at least 30.5 cm (12 in) in length on their bines, trellising can begin. Hops are typically trained by hand with two to three bines per coir twine. They are then wrapped around the twine clockwise, as it is their growth habit. If there are not enough bines present when training, or if bines fall off the trellis system due to wind or other factors, another training event may be needed. Following training, excess bines and shoots are pruned away. Allowing the extra shoots at the base of the plant increases pest pressure, and consequently, energy may be taken away from the main bines. Some cultivars may have a more upward growth habit and require little assistance in training. Additionally, basal growth can be removed with a chemical defoliant to prevent disease (Neve, 1991).

Just as with any successful crop, integrated pest management is required for hops. The first line of defense against insects and diseases is selecting a cultivar with good resistance. Common insect pests found on hops in the Southeastern United States include spider mites, whiteflies, caterpillars, thrips, and aphids. Spider mites and whiteflies are known to have the most "potential to become serious pests of commercial crops" (Smith et al., 2016). Companion plants such as grass, *Brassica*, and meadow flowering plants can be used in between rows to reduce some pest stress (Cambell, 2019). Common diseases to scout for on hops include powdery mildew, downy mildew, *Verticillium* wilt, and mosaic viruses. Purchasing clean rhizomes or containerized transplants as well as managing insect vectors may be the best way to prevent viruses in hops. While virus infection of hops may not substantially decrease cone quality in hops, it can reduce biomass and yields, and therefore preventing infection is imperative (Pistelli et al., 2018).

Some cultivars of hops may have more resistance to viruses and diseases than others. ‘Cascade’, for example, has a partial resistance to powdery mildew. However, further breeding for resistance should be conducted, as partial resistance may not be as effective over time as qualitative resistance, due to the adaptability of the fungus (Gent et al., 2017). Downy and powdery mildew can be managed with fungicide applications and the removal of basal leaves of the plants. In one study, there was no evidence of reduced α-acids by removing basal leaves as a preventative, but this could also vary with cultivar and environment. Although a late application of fungicide can affect yield and cone quality, it is sometimes practiced with the concern of the overwintering of downy and powdery mildew. However, if fungicide is applied during periods of greatest cone susceptibility and the canopy is properly managed, late application may not be needed. Additionally, overwintering *Podosphaera macularis* was not found in the soil without late fungicide applications during this study (Gent et al., 2016).

1.5.3 Harvest Methods

The timing of harvest should also be considered as it can affect the aroma quality of the cones depending on the harvest year and overall potential of the plants (Hagemann et al., 2024). In the Southeastern United States, hops are ready to be harvested from early August to mid-September, sometimes earlier or later, depending on cultivar and location. Cones are harvested when they reach full size, are still green, and have a dry and paper feel. Additionally, they should have a floral and hoppy aroma (McWhirt et al., 2021). Hops can be harvested by hand, which is very tedious and requires a lot of labor. They can also be harvested mechanically, in which entire hop plants are fed into a picking machine and the cones are separated from the vegetative matter (Neve, 1991). This method is utilized mostly by commercial growers, as the initial cost can be pricey.

1.6 Post-harvest

Following harvest, hops are dried until cones reach 8 – 12% moisture content. Moisture levels greater than 12% can result in decomposition or rot. Alternatively, drying below 8% can produce brittle cones with increased oxidation. After drying, hops are then packaged in vacuum sealed bags and can be stored for up to 12 months in a cooler of -4.44 to -2.22°C (Dodds, 2017). After properly drying hops, they can be assessed for a variety of factors to determine oil content, α− and β-acids, aroma profile, and ultimately the overall quality of the cones.

The α-acids, such as cohumulone and *n*- + adhumulone, are compounds within hop cones that provide bitterness to beer. β-acids, such as colupulone and *n*- + adlupulone, provide flavor and/or aroma (Danenhower et al., 2008). The percent content of each of these compounds varies by cultivar. For example, typical ranges for the cultivar 'Cascade' are 4.5 – 7.0% total α-acids and 4.8 – 7.0% total β-acids (Haas, 2022).

A proper ratio of acids as well as an aroma profile that is true to cultivar determines the cone quality. There are several methods for analysis. One method for profiling hops is using human sensory panels. For example, a descriptive analysis of dry hopped beer samples can be performed. In this method, training is provided for a group of panelists in which they are given a list of aromas to identify. Panelists are then presented with samples to taste and provide descriptors for each. Some common aromas can include pine-sol, garlic, cheesy, hay or grassy, orange, raisin, grapefruit, green tea, wet wood, lemon, herbal, and mint depending on cultivar. These notes can be detected across both beer samples and whole cone hops for the same cultivar, even with the brewing process changing the aroma slightly (Donaldson et al., 2012). Hop cone hand evaluations (in which cones are crushed and warmed through the rubbing of hands) alongside beer or hop tea samples may also be useful to further understand aroma profile building during panels.

Extractions and chemical analysis is commonly used for profiling hops. Concentration of α− and β-acids within hops can be analyzed using high performance liquid chromatography (HPLC), in which subsamples of cones are ground, dissolved, diluted, and injected into an HPLC machine and compared with a standard solution containing a known concentration of compounds (American Society of Brewing Chemists, 2008).

1.7 Study Objectives and Hypothesis

The overall goal for this study is to evaluate crop management strategies for the establishment of hop production in Alabama.

The specific objectives of this study include:

a) To evaluate the effect of mulching strategies on hop growth, development, and yield.
b) To compare the performance of different cultivars and trellis systems for hop growth, development, yield, and cone quality.

In the state of Alabama, hop growth and yield will be impacted by different mulching treatments. Additionally, biomass accumulation, yield, and cone quality of different cultivars will be impacted by the use of a V-trellis system in comparison to a straight trellis system. Therefore, this study has the following hypothesis: The use of mulching systems can increase biomass and yield, even in subtropical environmental conditions, where heat and/or stress conditions may affect cultivar performance. Simultaneously, trellis system may have a positive effect on yield or cone quality.

Chapter 2: Evaluation of Hop Performance Under Three Mulching Systems

2.1 Introduction

Hops (*Humulus lupulus* L.) are dioecious, perennial climbing plants in the family Cannabaceae, commonly grown in temperate regions (Jastrombek et al., 2022; Bocquet et al., 2018). These plants produce fast-growing twin stems known as bines, which can grow 25 cm per day and reach heights of approximately 7.6 m (Pearson, 2013; Sirrine, 2014). Female plants produce cones with lupulin glands that synthetize a complex mixture of secondary metabolites, including terpenes, bitter acids, and polyphenols, which are essential contributors to the aroma, bitterness, and flavor of beer (Rodolfi et al., 2019; Bocquet et al., 2018).

Globally, hops are cultivated in major regions such as China, Europe, Canada, and the United States (U.S.). In the U.S., commercial hop production is mainly focused on the Pacific Northwest (i.e., Washington, Idaho, and Oregon) (USDA, 2024). In 2024, these three states produced about 39.5 million kg of hops from 18,127 ha, with a total crop value of $446 million (USDA, 2024). Production outside the Pacific Northwest accounts for only 2% of the U.S. commercial hop production area (USDA, 2024). However, interest in hop cultivation beyond this region continues to rise, driven by the rapid expansion of the craft beer industry and the growing consumer demand for locally sourced agricultural ingredients (Brewers Association, 2024). As a result, efforts to establish local hop production in the Southeastern U.S. are increasing, opening new opportunities for growers in Alabama to support the region's emerging brewing industry (Silva and Danderson, 2022).

Growing hops in the Southeastern U.S. presents several challenges associated with environmental conditions, including high summer temperatures (especially during July and August), high humidity, heavy rainfall, and soils that are sandy, clayey, or acidic (Eck et al., 2020;

Mylavarapu et al., 2014). These conditions increase stress on plants and elevate disease and weed pressure, often resulting in reduced plant vigor and lower yields (Ericksen et al., 2020).

Under this scenario, mulching is a promising management strategy to mitigate these environmental challenges. The use of mulches such as pine bark or black fabric groundcovers can enhance soil moisture retention, regulate soil temperature, suppress weeds, and reduce runoff, providing protection for plants exposed to intense heat and fluctuating rainfall patterns (Iqbal et al., 2020). Regarding soil quality and contents, in a study investigating the effects of bark mulch on hops, grapes, and olives, it was found that composted bark mulch provided increased organic carbon, microbial biomass, and potassium availability in the soil for hop plants. Additionally, for olive trees, bark mulch slightly raised the soil temperature during establishment, stimulating root activity and accelerating nutrient uptake, resulting in increased early tree growth by 35% (Bound, 2014). When considering breathable fabric mulch in apricot orchards, soil moisture content was increased by 17.09%, resulting in quicker fruit ripening and higher fruit quality (Li et al., 2025). However, research on the effects of different mulching systems on hop production under Southeastern U.S. conditions remain limited.

The objective of this study was to evaluate the effects of two mulching systems (pine bark and black fabric) compared with a bare ground control on hop growth and yield in Alabama. This research aims to provide science-based recommendations to support sustainable hop production in non-traditional, subtropical environments and strengthen local supply chains in the Southeastern U.S.

2.1 Materials and Methods

2.2.1 Experimental Design and Field Management

Field experiments were conducted at Auburn University's E.V. Smith Research Center in Shorter, Alabama (32°26'54" N, 85°54'14" W) from April to July in 2021 and 2022. The site has a humid subtropical climate characterized by hot, wet summers and mild, dry winters (McNulty and Gavazzi, 2021).

The experiment was conducted using a randomized complete block design with three replications. Treatments included a pine bark mulch, a black fabric, and bare ground. All treatments were applied at site preparation. Treatments were applied within rows and extending across the entire plot (Figure 2.1). Each experimental unit consisted of a single row of ten hop plants ('Cascade') spaced 76 cm apart.

Figure 2.1. From left to right, bare ground, pine bark, and black fabric mulching treatments.

Virus-free, plug transplants of the cultivar 'Cascade' were used. Transplants were potted and grown in a greenhouse for one month following the procedures described by Agehara et al., 2020b. Hops were planted approximately 3 years prior to the experiment. A V-trellis system, 3.7 m in height, was constructed to support bine training (Figure 2.2). Hop yard establishment and trellis construction were conducted according to Agehara et al., 2020a.

Figure 2.2. Trellis set up/training and mulching applications.

Crop management practices, including soil preparation, irrigation, fertilization, and pest, weed, and disease management were consistent across treatments and followed recommendations from the Southeastern U.S. Vegetable Crop Handbook (Kemble, 2020). Once plants reached approximately 30 cm in height, four bines per plant were selected and trained on the V-trellis (Figure 2.2). Plants were routinely pruned to maintain the appropriate number of bines and to keep the plant base clear to prevent tangling and disease.

2.2.2 Data Collection

Plant height was measured weekly over a 10-week period by recording the height of the tallest bine in each plot for every treatment. The tallest bine was selected to be an indicator of the plant's overall health and vigor. This method of height collection was implemented for efficiency within the experiment.

Weather conditions, including daily minimum, maximum, and average air temperature, rainfall, and solar radiation, were recorded from April to July in both years (2021 and 2022) using an on-site weather station.

Hop plants were harvested on June 30 and July 22 in 2021 and on July 5 in 2022. In both years, each plant was cut from the trellis, and cones were hand-harvested. Fresh cone yield (FCY) was weighed immediately after harvest, oven-dried at 60°C to a target moisture content of 8 – 12%, and reweighed to determined dry cone yield (DCY) (Agehara et al., 2020b). Fresh and dry cone yields were recorded separately by treatment and plot.

For biomass assessment, all vegetative material remaining after cone harvest was weighed to determine fresh biomass yield (FBY). Samples were then oven-dried at 60°C until a constant weight was reached to determine dry biomass yield (DBY).

2.2.3 Statistical Analysis

All data was analyzed using RStudio (v.4.4.0; RStudio Team, 2020). Daily measurements of air temperature, rainfall, and solar radiation were analyzed to compare environmental differences between both years. A Mann-Whitney U test and a t-test were used to compare weather variables. The Mann-Whitney U test was used to account for skewed, non-normal data (such as rainfall), while the t-test was used to account for mostly normal data, such as temperature.

Bine growth data was analyzed using a generalized linear mixed model to account for deviation from normality, as indicated by Q-Q plots and confirmed by the Shapiro-Wilk test. Heteroscedasticity was assessed using residuals versus fitted value plots. Fixed effects included treatment (bare ground, pine bark, and black fabric), year (2021 and 2022), week (Weeks 1-10), and their interactions, while block was included as a random effect.

A linear mixed-effects model was used to analyze fresh cone yield (FCY), dry cone yield (DCY), fresh biomass yield (FBY), and dry biomass yield (DBY). Fixed effects included treatment, year, and their interaction, while block was included as a random effect. Residual normality was confirmed using Q–Q plots and the Shapiro–Wilk test, and homoscedasticity was evaluated using residuals versus fitted value plots.

Analysis of variance (ANOVA) was performed on all variables, and multiple comparisons of least squares means were performed using Tukey's honestly significant difference (HSD) test at a *p*-value of 0.05.

2.3 **Results**

2.3.1 Weather Conditions

Seasonal weather patterns during the hop growing seasons of 2021 and 2022 are illustrated in Figure 2.3. Average daily air temperature was higher in 2022 (24.1°C) than in 2021 (22.7°C) ($p \leq 0.05$). Solar radiation also differed between years, with 2022 receiving greater daily radiation (11.4 MJ m^{-2} day^{-1}) compared to 2021 (10.4 MJ m^{-2} day^{-1}) ($p \leq 0.05$). Total rainfall in 2021 (585 mm) was higher than 2022 (410 mm).

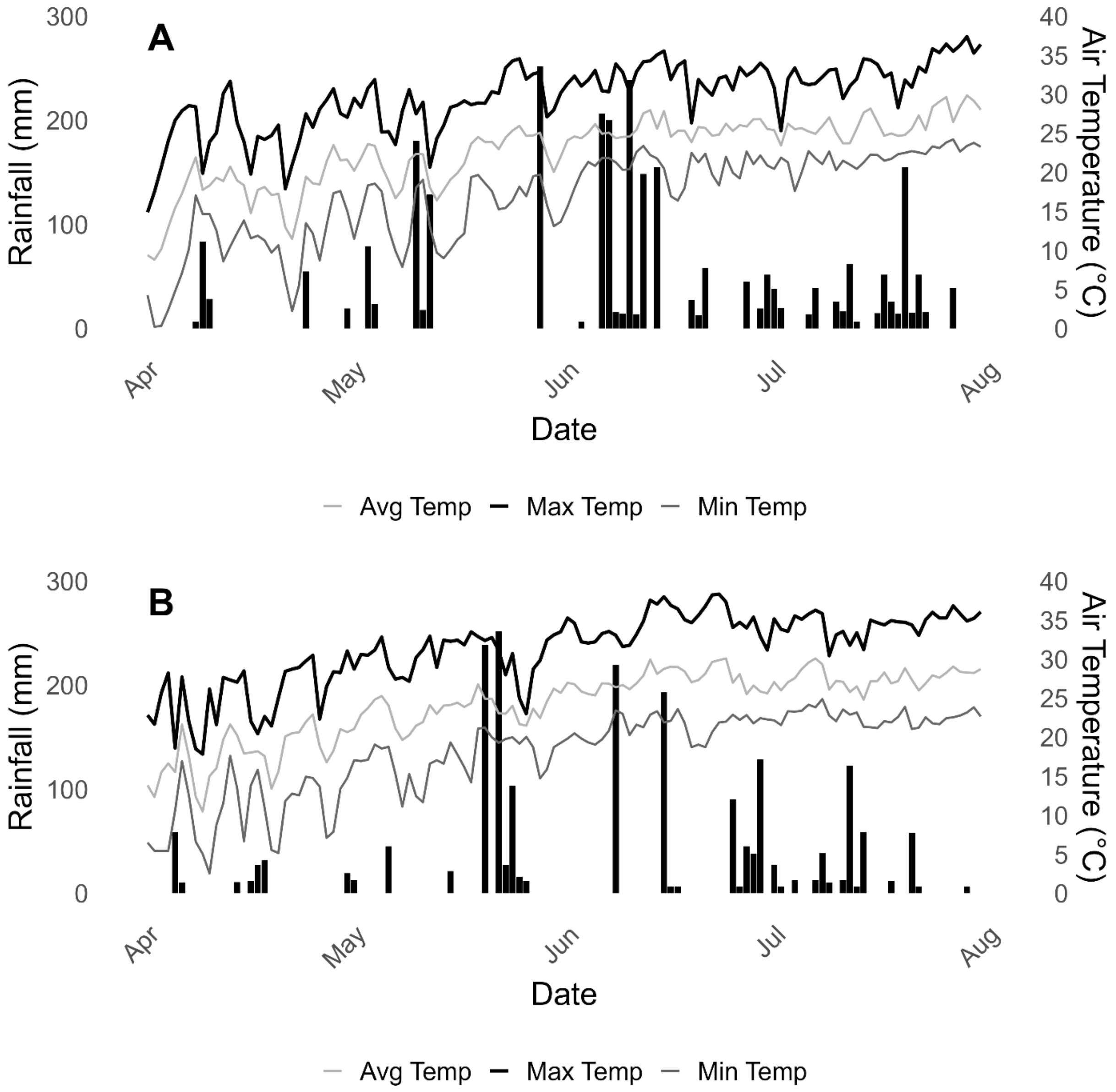

Figure 2.3. Daily weather variation showing minimum (Min Temp), average (Avg Temp), and maximum (Max Temp) air temperatures (°C) and rainfall (mm) from April 1 to July 31 in 2021 (A) and 2022 (B).

[i] 1 mm = 0.0394 in

[ii] °F = (°C * 1.8) +32

2.3.2 Bine Growth

It should be noted that the structural limitation of trellis height prevented further vertical growth and should be considered when interpreting bine growth data. Hop bine height was significantly impacted by the two-way interaction between year and week ($p \leq 0.01$), and the three-way interaction among year, treatment, and week ($p \leq 0.001$).

Hop growth followed a rapid elongation phase during the first 5 weeks, with plants in 2022 generally reaching greater heights earlier in the season compared to those in 2021 (Figure 2.4). In 2022, bines grown on the black fabric treatment had the most rapid early growth, reaching 318 cm by week 4 and achieving full trellis height (366 cm, 3.7 m) by week 5. Bines under the bare ground treatment reached 294 cm by week 5, while those grown on pine bark treatment measured 268 cm. In contrast, plants in 2021 were shorter during the same period for all treatments, with week 5 heights ranging from 180 cm on the pine bark treatment to 237 cm on the black fabric treatment.

In week 7, all treatments in 2022 exceeded 338 cm, whereas 2021 treatments ranged from 280 cm (pine bark) to 308 cm (black fabric). By the end of the 10-week period, most treatments in both years had reached or nearly reached full trellis height (366 cm, 3.7 m).

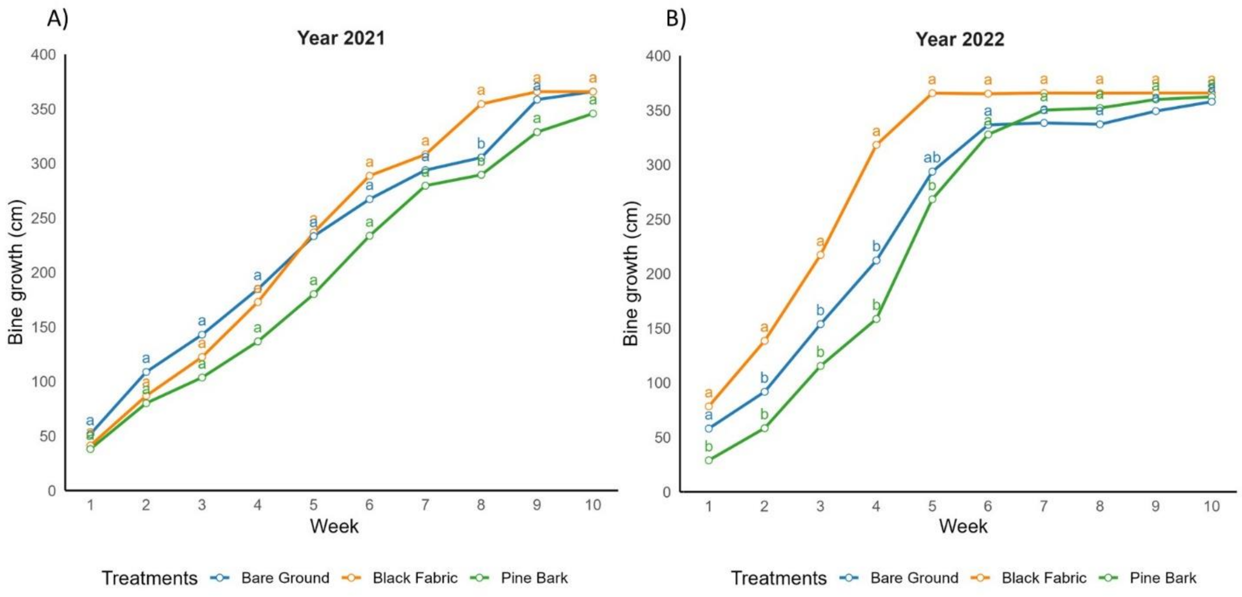

Figure 2.4. Hop bine growth over a 10-week period in 2021 (A) and 2022 (B) under three treatments: bare ground, black fabric, and pine bark.
[i] Different letters within the same week indicate statistically significant differences among treatments according to Tukey's test ($p \leq 0.05$).

2.3.3 Fresh and Dry Cone Yield

Both FCY and DCY were significantly affected by the interaction between year and treatment ($p \leq 0.05$). Overall, average yields for all treatments were significantly higher in 2021 than in 2022 ($p \leq 0.05$). Average FCY in 2021 was 673.0 ± 35.2 kg ha^{-1}, compared with 320.0 ± 40.0 kg ha^{-1} in 2022. Similarly, DCY averaged 186.9 ± 9.7 kg ha^{-1} in 2021 and 86.7 ± 11.4 kg ha^{-1} in 2022.

Table 2.1 presents the FCY and DCY of hops in 2021 and 2022 under different treatments. In 2021, there were no significant differences among treatments in FCY ($p > 0.05$), with values ranging from 634.1 ± 58.5 kg ha^{-1} (bare ground) to 725.8 ± 86.8 kg ha^{-1} (pine bark). In contrast, in 2022, black fabric resulted in the highest FCY (445.7 ± 69.1 kg ha^{-1}), significantly greater than pine bark (211.6 ± 15.7 kg ha^{-1}), while bare ground had intermediate values (302.8 ± 15.1 kg ha^{-1}).

There was a similar trend for DCY. In 2021, DCY did not differ significantly among treatments ($p > 0.05$), ranging from 176.2 ± 16.2 kg ha^{-1} (bare ground) to 201.6 ± 24.1 kg ha^{-1} (pine bark). However, in 2022, black fabric produced the highest DCY (122.5 ± 19.0 kg ha^{-1}), significantly higher than pine bark (53.9 ± 0.4 kg ha^{-1}), with bare ground again having intermediate values (83.7 ± 3.9 kg ha^{-1}).

Table 2.1. Fresh and dry cone yields of hops in 2021 and 2022 under different treatments.

Treatments	**FCY[i] (kg ha-1)**	
	2021	**2022**
Bare ground	634.1 ± 58.5[ii] a[iii]	302.8 ± 15.1 ab
Pine bark	752.8 ± 86.9 a	211.6 ± 15.7 b
Black fabric	659.0 ± 40.2 a	445.7 ± 69.1 a
Average of Treatments	673 ± 35.2 A[iv]	320.0 ± 40.0 B
Treatments	**DCY[v] (kg ha-1)**	
	2021	**2022**
Bare ground	176.2 ± 16.2 a	83.8 ± 3.9 ab
Pine bark	201.6 ± 24.1 a	53.9 ± 0.4 b
Black fabric	183.1 ± 11.2 a	122.5 ± 19.0 a
Average of Treatments	186.9 ± 9.7 A	86.7 ± 11.4 B

[i] FCY: fresh cone yield.

[ii] Values are presented as mean ± standard error.

[iii] Values followed by similar lowercase letters among treatments within year indicate no significant difference ($p > 0.05$) according to Tukey's test.

[iv] Values followed by similar uppercase letters among years indicate no significant difference ($p > 0.05$) according to Tukey's test.

[v] DCY: dry cone yield.

2.3.4 Fresh and Dry Biomass Yield

FBY was significantly affected by the main effect of year ($p \leq 0.05$), whereas DBY was not significantly influenced by year, treatment, or their interaction ($p > 0.05$). Average FBY in 2021 (1,103.3 ± 71.9 kg ha^{-1}) was significantly higher than in 2022 (547.0 ± 64.3 kg ha^{-1}) ($p \leq$

0.05). In contrast, DBY did not differ significantly between 2021 (422.0 ± 20.0 kg ha^{-1}) and 2022 (336.3 ± 38.7 kg ha^{-1}) ($p > 0.05$).

Table 2.2 presents the FBY and DBY of hops in 2021 and 2022 under different treatments. In 2021, FBY did not differ significantly among treatments ($p > 0.05$), with yields ranging from 941.2 ± 98.3 kg ha^{-1} under pine bark mulch to 1,254.2 ± 50.5 kg ha^{-1} under black fabric. In 2022, the FBY ranged from 656.5 ± 114.9 kg ha^{-1} (black fabric) to 455.1 ± 116.0 kg ha^{-1} (bare ground). However, these differences were not statistically significant ($p > 0.05$).

DBY exhibited a similar pattern. In 2021, DBY ranged from 374.7 ± 23.0 kg ha^{-1} under pine bark to 485.8 ± 17.1 kg ha^{-1} under black fabric. In 2022, DBY values ranged from 294.4 ± 75.0 kg ha^{-1} under bare ground to 398.4 ± 69.8 kg ha^{-1} under black fabric.

Table 2.2. Fresh and dry biomass yields of hops in 2021 and 2022 under different treatments.

Treatments	**FBY[i] (kg ha^{-1})**	
	2021	**2022**
Bare ground	1,114.5 ± 159.0[ii] a[iii]	455.1 ± 116.0 a
Pine bark	941.2 ± 98.3 a	529.4 ± 112.1 a
Black fabric	1,254.2 ± 50.5 a	656.5 ± 114.9 a
Average of Treatments	1,103.3 ± 71.9 A[iv]	547.0 ± 64.3 B
Treatments	**DBY[v] (kg ha^{-1})**	
	2021	**2022**
Bare ground	405.5 ± 26.1 a	294.4 ± 75.0 a
Pine bark	374.7 ± 23.0 a	316.0 ± 66.9 a
Black fabric	485.8 ± 17.1 a	398.4 ± 69.8 a
Average of Treatments	422.0 ± 20.0 A	336.29 ± 38.7 A

[i] FBY: fresh biomass yield.

[ii] Values are presented as mean ± standard error.

[iii] Values followed by similar lowercase letters among treatments within year indicate no significant difference ($p > 0.05$) according to Tukey's test.

[iv] Values followed by similar uppercase letters among years indicate no significant difference ($p > 0.05$) according to Tukey's test.

[v] DBY: dry biomass yield.

2.4 Discussion

The interaction between year and treatment revealed that benefits of black fabric were pronounced during more stressful conditions (higher temperatures and lower rainfall). For example, plants grown under black fabric resulted in taller plant heights in the first 5 weeks of 2022 compared to the other treatments, indicating rapid bine growth. This is likely due to regulated soil temperature and moisture under the fabric. This is more favorable for root growth and nutrient uptake, and accelerates early-season growth, as demonstrated in a previous study investigating polypropylene fabrics for mulching (Adamczewska-Sowińska et al., 2025). Additionally, bine growth in 2021 indicated that hop plants reached approximately 366 cm (3.7 m, trellis height) by week 9, as opposed to week 5 in 2022. This emphasizes less vigorous growth for black fabric in the first year compared to the second. This could be due to the improvement of soil structure and water dynamics, and therefore nutrient cycling, that is provided by inorganic mulches (Mubaraka et al., 2022).

Collectively, hop performance and yield in 2021 surpassed that of 2022, perhaps due to cooler temperatures and higher rainfall. It is possible that the conditions of the second year may have led to stressed plants, and therefore, poorer development of vegetative growth and cones. A previous study demonstrates climate-induced decline in quality and quantity of hops under stressful climatic conditions. Trends in recent years have exhibited rising temperatures and insufficient moisture, reducing yields. As cones mature during the hot, summer months, α- and β-acid content is negatively impacted (Mozny et al., 2023). Furthermore, temperature and photoperiod affect flower initiation, and higher temperatures and solar radiation in 2022 may have caused in a disruption of the reproductive phase, resulting in inadequate flowering and cone formation (Bauerle, 2019).

Because hops grown under the black fabric treatment exhibited taller bine growth and yield compared to the other treatments in the second year, soil moisture retention and temperature regulation may be assumed. Forward (2017) investigated similar mulching treatments (i.e., landscape fabric, woodchips, straw, and bare ground) and found that the landscape fabric provided the most soil moisture retention and weed suppression, resulting in increased biomass and yield due to reduced drought stress and soil nutrient competition. This study also found that woodchips and straw had higher soil temperature regulation and stability due to better insulation. However, these treatments had lower soil moisture retention and weed suppression, increasing instances of drought and competition. Therefore, woodchips and straw resulted in lower yields compared to fabric mulching. The bare ground treatment had the lowest moisture retention, weed suppression, and temperature regulation, and therefore lowest yield and performance, which contrasts to our study, in which bare ground produced better yields than pine bark in 2022. This may be due to earlier warming of the soil for bare ground, resulting in quicker development and maturation (Chalker-Scott, 2021).

Without direct analysis of the effects of temperature, rainfall, and solar radiation on growth and yield, and without soil moisture and temperature data, impacts of the environment can only be inferred. Importantly, these hops had been planted 3 years prior to the experiment, and therefore, yield potential may have dropped by 2022 (when plants were approximately 5 years old) due to long-term exposure to high humidity and disease pressure (and potential crown rot), in addition to or regardless of climatic stressors (Holland et al., 2023).

2.5 Conclusion

Mulching systems, particularly black fabric, could enhance hop growth and yield in the Southeastern U.S., where environmental conditions can put stress on hop productivity. While environmental differences (and other possible factors such as plant age) between years had the strongest influence on performance, the interaction between year and treatment highlights the importance of selecting appropriate mulching strategies based on seasonal variability. The increase in weekly bine growth and yield under black fabric mulching in the second year provides valuable insights for growers seeking to optimize hop production in Alabama and similar regions. Future research should include direct measurements of soil moisture and temperature to clarify the mechanisms behind mulching effects, as well as analyzing the direct effects of climate on plant growth and yield. Additionally, testing other mulching options and mulch combinations (especially across several years) to optimize growth, yield, and protection from environmental conditions would be beneficial.

Chapter 3: Cultivar Performance and Trellis Systems Strategies for Hop Production in Subtropical Environmental Conditions

3.1 Introduction

Hops (*Humulus lupulus*) are dioecious, perennial plants grown throughout the world for their strobili to be used in the brewing of most beers. This crop is often propagated via rhizomes, which are portions of rootstock that can be planted in the fall or spring (McWhirt et al., 2021). This method of propagation is preferred by many farmers, as it is one of the cheapest options and requires less care, but has a greater risk of introducing diseases and viruses to the field (Butzler et al., 2021). Live plug or containerized transplants, however, are less risky when it comes to disease presence and are quicker to establish root systems (Butzler et al., 2021). Therefore, this method of propagation was chosen for this study.

In the initial years after planting, hop plants establish their root systems and gradually increase their yield and cone quality, taking up to three years before reaching their maximum potential (Brooks et al., 1961; Hagemann et al., 2024). Cone size will also gradually improve in the first few years, and it can be expected that cone size and mass may not be uniform until plants are fully established (Guimarães, 2020). This experiment includes the first two years of the hops' establishment, and data should be interpreted with these considerations in mind.

Within the United States, hops are most commonly grown in Washington, Oregon, and Idaho (USDA, 2024) due to their favorable conditions for production. This includes longer daylengths during the growing season and a more temperate climate, which is preferred by the crop (Jastrombek et al., 2022; Bocquet et al., 2018). While the desire to have local hops in

Alabama increases, there are many challenges when it comes to growing these plants in a subtropical climate.

Depending on the cultivar used and location of production, hops need between 15 and 17 hours of light (Thomas and Schwabe, 1969). Due to a daylength of 11 – 14 hours in the location of this experiment (Mobile, Alabama), supplemental lighting must be provided. This extended daylength will delay the flowering of the plants, allowing the accumulation of a greater amount of biomass, therefore increasing yield potential (Leles et al., 2023).

Another challenge in Alabama is the heat stress and disease pressure. During this experiment in Mobile, Alabama, air temperature peaked in July and August, reaching about 37°C, which can decrease photosynthetic activity, yield, and cone quality (Eriksen et al., 2020; Mozny et al., 2023). Humidity can also be an issue in hop production, causing an increase in disease and weed pressure, often resulting in reduced plant vigor and yield (Ericksen et al., 2020). Additionally, this increase in humidity and disease pressure can lead to crown rot in the hops, reducing their productivity from 10 – 15 years to as little as 5 – 7, at which point plants must be replaced (Holland et al., 2023).

One of the best ways to mitigate many of these challenges is proper cultivar selection. Different cultivars can vary in adaptability to certain climates, as well as impact overall yields, cone size, and cone composition (Alas, 2022). It is important to choose a cultivar that is well-adapted to the growing environment. Additionally, the cultivar(s) should produce desirable yields and the target cone composition. The level of bitterness (from α-acids) and/or unique flavors (from β-acids and essential oils) that meet the market's (brewer's) interest should be considered. Studying the response of multiple cultivars (i.e., their growth and yield in response to the environment) as well as their resulting cone composition in this region can be extremely valuable for growers' selection decisions.

The four cultivars evaluated in this experiment during 2024 are 'Cascade', 'Chinook', 'Magnum', and 'Neo1'. Cultivar 'Nugget' was used instead of 'Neo1' in 2025. All cultivars were selected for their desirability by brewers and potential to adapt to Alabama climate. Heat tolerance, for example, is a desirable trait for the region and is common in cultivars with an increased abiotic stress tolerance, such as by maintaining thylakoid membrane integrity and Rubisco activase activity (Eriksen et al., 2020).

Particularly, 'Cascade' is a well-known high performer for the region (Contin et. al., 2023; Neves et al., 2024; Eriksen et al., 2020) and was selected for further evaluation and comparisons against other cultivars as well as within the two different trellis systems. 'Chinook' can also tolerate warm, humid climates (Eriksen et al., 2020) and was selected for this reason along with its versatility in brewing (Haas, 2022). 'Magnum' was selected for its large cones and resistance to disease (Haas, 2022). 'Neo1' was selected for its previous selection for the southeast and native range to United States (Pearson et al., 2016). This cultivar was used in a particular experiment in Florida, in which it performed adequately under an open greenhouse system, especially in the second year (Pearson et al., 2016). Finally, 'Nugget' was selected for its potential for adaptability to the climate of the Southeastern United States, as well as its versatility in brewing beer (Neves et al., 2024; Haas, 2022).

Besides having ideal climatic conditions and cultivar selection, hop production is most successful with proper trellis implementation. The type and height of the trellis used in hop production can impact both biomass and yield. Trellis heights can range from 3 to 6 m tall, although 4.5 m is typical and used in this experiment (Dodds, 2017). Yields have been improved in previous studies when used on a taller trellis system than a shorter one, increasing up to 80% (Darby, 2004). The two trellis types commonly used in hop production are straight trellises and V-trellises. While V-trellises can be more expensive in their initial building costs due to more materials being used (Agehara et al., 2020), they can increase yield substantially, especially when combined with taller height (i.e., Darby, 2004; Gallardo et al., 2025). This study will investigate the use of these two trellis systems further as previous studies may not fully reflect its potential and performance in Alabama.

The objective of this study was to evaluate the effects of cultivar selection and trellis type on hop growth, cone yield, and cone quality in Alabama. This research aims to provide science-based recommendations to support sustainable hop production in non-traditional environments and strengthen local supply chains in the Southeastern U.S.

3.2 Materials and Methods

3.2.1 Experimental Design

Field experiments were conducted in 2024 and 2025 at the Ornamental Horticulture Research Center from Auburn University in Mobile, AL. A split plot design, with cultivar treatments (subplots) being arranged within trellis treatments (plots), was used in this study, consisting of three repetitions (Table 3.1). Trellis system treatments consisted of a straight trellis treatment and a V-trellis treatment. Cultivar treatments consisted of ‘Cascade’, ‘Chinook’, ‘Magnum’, and ‘Neo1’ (2024) or ‘Nugget’ (2025).

Table 3.1. Split plot design with arrangement of treatments.

Straight trellis	Straight trellis	V-trellis	V-trellis	V-trellis	Straight trellis
6D CAS[i]	**5D** MAG	**4D** CHI	**3D** NEO / NUG	**2D** CAS	**1D** CHI
6C CAS	**5C** MAG	**4C** CHI	**3C** NEO / NUG	**2C** CAS	**1C** CHI
6B CHI[ii]	**5B** NEO[iv] / NUG[v]	**4B** MAG	**3B** MAG	**2B** NEO / NUG	**1B** NEO / NUG
6A MAG[iii]	**5A** CAS	**4A** MAG	**3A** CAS	**2A** CHI	**1A** NEO / NUG

[i] CAS = ‘Cascade’
[ii] CHI = ‘Chinook’
[iii] MAG = ‘Magnum’
[iv] NEO = ‘Neo1’
[v] NUG = ‘Nugget’

3.2.2 Site Description and Preparation

The hop yard was installed in 2024, and therefore, hop plants were in their first and second season during the period of the experiment. The soil type for this field was described as sandy loam (or BCg) according to the USDA’s Millhopper series and soil testing by Auburn University Soil Testing Laboratory (Soil Survey Staff, 2025). Weather conditions of the region were classified as a *Cfa* (humid subtropical) climate, with no significant precipitation difference between seasons (Koppen, 1931). The hop yard consisted of wooden poles 20-feet tall buried at a depth of 1.5 m for the trellising systems. Wooden poles were spaced 3.7 m apart from east to west and 9.8 m apart from north to south within the field. Cables were strung across the tops of each pole to hold the coir twine for trellising (Agehara et al., 2020). Trellis systems were oriented from north to south.

Containerized transplants were acquired from Great Lakes Hops (Zeeland, Michigan, USA) in 2023 and overwintered in a greenhouse in a pine bark potting mixture. Plantlets of ‘Cascade’, ‘Chinook’, ‘Magnum’, and ‘Neo1’ were planted on March 14th, 2024, with 10 plants per subplot at 76 cm spacing. The subplots with the cultivar ‘Neo1’, however, due to loss from mite damage, had only 8 plants per subplot, which were centered within the subplot. Transplants of 'Neo1' did not survive the environmental conditions of the experiment and were replaced by cultivar 'Nugget' in 2025, in which rhizomes were planted on May 28th, 2025. Prior to rhizome planting, 80 lb/acre of N using a NPK fertilizer of 20-20-20 was applied and the soil corrected for pH using soil recommendations provided by the Auburn University Soil Testing Laboratory.

On February 22nd, 2024, lighting cables were installed along the length of each row and connected on the north side to solar panels. Deep red/white bulbs (Total Energy Group, Carpinteria, California, USA) were installed every 6 m in each row (Leles et al., 2023).

Irrigation water was supplied using two lines of drip tape, installed one on either side of each row. Drip tapes were 5/8-inch (16 mm) using a GPM of 0.450 per 30 m and a PSI of 8 (508-12-450 T-Tape, Rivulis, San Diego, California, USA). Drip tapes were connected at the south side of each row to an injector from which fertilizer was applied. Black fabric mulch was laid for weed control early March 2024.

3.2.3 Crop Management

Irrigation water was applied up to twice a day, beginning with approximately ½ gallon per week, increasing to ½ gallon per plant per day in May, and finally increasing to 1 gallon per plant per day once the top of the trellis had been reached by most of the hop plants. Fertilization initiated 2 weeks after planting in 2024, and at emergence in 2025. The previously mentioned 20-20-20 fertilizer was dissolved in water and applied via drip irrigation daily to supplement the plants with 20 lbs. of nitrogen per acre (50 ppm) and increased mid-May to 75 lbs. of nitrogen per acre (187.5 ppm) in 2024. In May of 2025, fertilization increased to 100 lbs. of nitrogen per acre (250 ppm) (Gingrich et al., 2000). Plants stopped being fertilized during the late flower or early cone stages of the plants to slow vegetative growth and avoid nitrogen accumulation in developing cones. In 2025, a liquid lime (Cal-Flo, Burnett Lime Co., Campobello, South Carolina, USA) was applied in July to correct low pH of about 4.5. A calcium nitrate fertilizer was then used until harvest to keep the pH around 6.0.

Supplemental lighting was provided beginning at dusk to extend day length to from 11-14 hours to approximately 16-18 hours. Lighting was supplied from emergence until most plants had accumulated significant biomass, which occurred at the end of June/early July of both years (Leles et al., 2023; Neve, 1991).

Trellising began on April 17th, 2024, and April 21st, 2025, once there was sufficient shoot growth and continued every one to two weeks until all plants were trained. Coir twine was used from the base of the plants to the trellis cables, with one line of twine for straight trellises and two lines of twine for V-trellises. Two bines per coir twine were selected based on average vigor and overall health to be trained. Shoot growth around the base of the plant was then pruned away. Plants within a straight trellis plot had two bines per plant trellised, while plants within a V-trellis plot had four bines per plant (Figure 3.1).

Figure 3.1. V-trellis (left) and straight trellis (right) systems established, with some of the 'Neo1' bines trained on the V-trellis.

3.2.4 Field Data Collection

Field evaluations included plant height, drone mapping and leaf area index collections to determine biomass accumulation, and photosynthesis performances using Li-Cor and Dualex machines. All measurements were recorded throughout the growing season at vegetative, flowering, and coning growth stages. Data on Nugget plants were not recorded due to minimal emergence rate. The fresh weight of cones, or fresh cone yield (FCY), was collected during harvest, followed by the weight of dried cones, or dry cone yield (DCY), which were dried at 60° C (~145° F) to approximately 12% moisture content (Dodds, 2017). Dried cones were placed in vacuum sealed bags and placed in freezer storage (32°F, 0°C) for lab evaluations.

Plant height measurements were taken in two random plants per subplot once the plants had been trained onto the trellis. Measurements occurred every other week from plants' emergence until all plants reached the maximum trellis height of 457 cm (4.6 m). During each data collection, the tallest bine was selected to be an indicator of the plant's overall health and vigor. This method of height collection was implemented for efficiency within the experiment.

Leaf area index, or LAI, was measured using the ACCUPAR LP-80 (METER Group, Pullman, Washington, USA). This device provides a non-destructive method of determining canopy growth and light interception in a group of plants (METER Group, 2025). Measurements were taken in two random plants per subplot. Measurements were recorded directly next to the plant, 15 cm (6 inches) from the plant, and 30.5 cm (12 inches) from the plant on the south end, followed by the same measurements on the west end (Figure 3.2). Measuring on the south and west ends of the plant allow for greatest shadow interception. LAI measurements were recorded every other week (at least one measurement per growth stage). In addition to LAI collections, drone imaging using the DJI RC Pro drone (DJI, Shenzhen, China) was performed on May 1st and June 21st, 2024, to visually represent the increase in biomass from early vegetative until early cone.

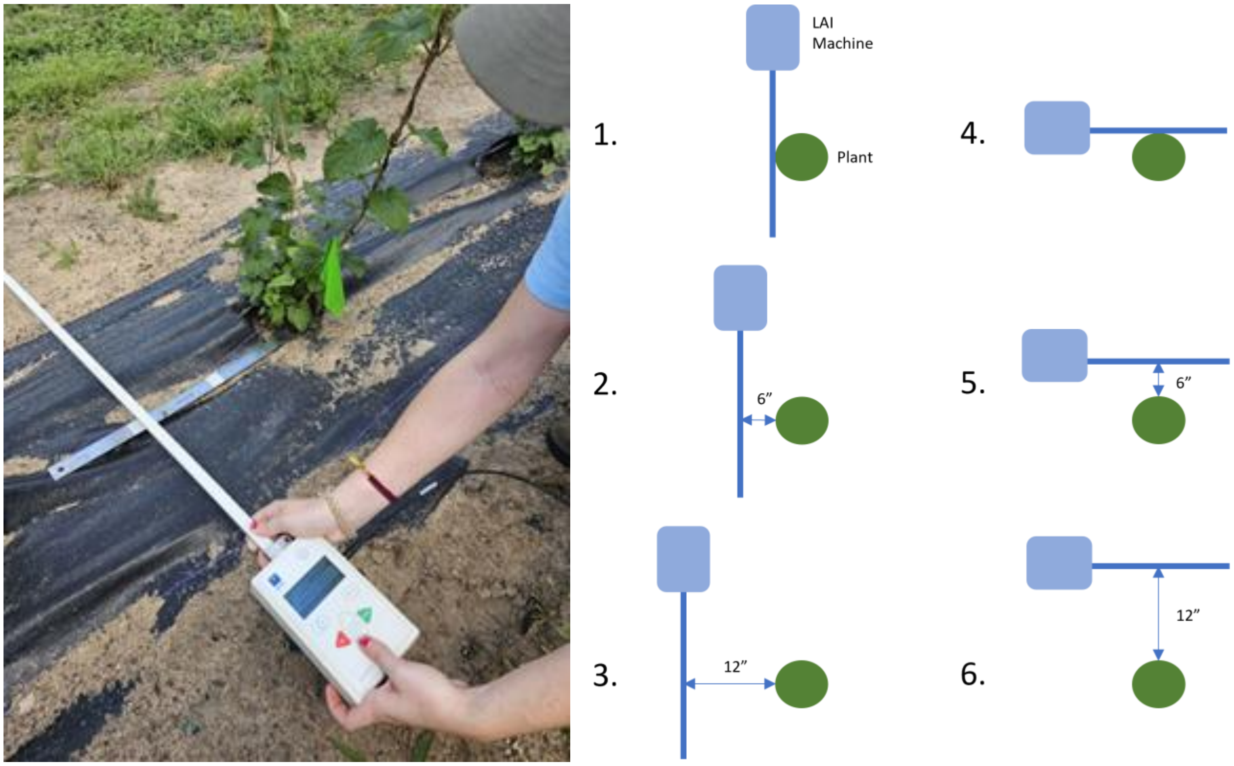

Figure 3.2. Example of ACCUPAR placement at 30.5 cm (12 in) from the plant on the south side (left) and LAI collection protocols for the six measurements per plant (right).

Photosynthesis parameters were collected using the LI-6800 Portable Photosynthesis System (Li-Cor, Lincoln, Nebraska, USA), and pigments were recorded with the Dualex (Pessl Instruments, Weiz, Austria). Photosynthesis parameters consisted of photosynthesis rate (*A*), stomatal conductance (gs), and electron transport rate (ETR) (Sukhov, 2024). In addition, the Dualex recorded chlorophyll index (Chl). In 2024, these measurements were taken at each growth stage. However, in 2025, photosynthetic and pigment data were only collected during the vegetative and cone stages.

Weather conditions for the area were collected using an on-site weather station and included maximum and minimum daily air temperature, maximum UV index, solar radiation, percent relative humidity, rainfall, and photoperiod.

3.2.5 Harvest Methods

On July 25th, 2024, all 'Cascade' subplots were harvested, as cones from this cultivar matured before the others. Cones were determined to be ready for harvest when they were full size, dry, and papery to the touch with a hoppy aroma (McWhirt et al., 2021). No 'Neo1' cones were harvested due to loss of plant material. Plants were harvested by cutting the top and bottom of each plant, and hop cones were hand-picked. On August 9th of 2024, 'Magnum' and 'Chinook' plants were harvested. In 2025, all plants were harvested at once using a Hop Harvester 1000 mechanical harvester (Steenland, New York, USA) on September 4th. Fresh cone yield in this year contains some leaf matter. This excess matter was kept in the fresh cone weight to account for the general loss of yield from using the mechanical harvester. However, final dry weights did not include any leaf matter and measured cones only. Actual yield loss was not quantified during this experiment. 'Nugget' plants were not harvested, as few had emerged since planting in May, and no cones were produced.

3.2.6 Sample Preparation and Injection for HPLC Analysis

To conduct analysis of α- and β-acids within the cones, high-performance liquid chromatography, or HPLC, was used. This was carried out with the Agilent 1260 Infinity II Manual Preparative LC System (Agilent, Santa Clara, California, USA). Ultraviolet detection was used to separate and quantitate cohumulone and *n*- + adhumulone (α-acid components), as well as colupulone and *n*- + adlupulone (β-acid components) in the hop cones (American Society of Brewing Chemists, 1990).

The standard method Hops-14 by the American Society of Brewing Chemists (2008) was used to perform all HPLC analyses. All chemicals were purchased from VWR International, LLC, Radnor, Pennsylvania, USA to perform the analysis unless otherwise specified. The mobile phase consisted of HPLC-grade methanol, ultra-pure water, and orthophosphoric acid in an 85:12:0.25 ratio. To create calibration curves for the analysis of the results, the ICE-4 international calibration extract was purchased from the American Society of Brewing Chemists (or ASBC, Saint Paul, Minnesota, USA) with a specified concentration of α- and β-acids. These concentrations are as follows: Cohumulone (10.98%), *n*- + adhumulone (31.60%), Colupulone (13.02%), *n*- + adlupulone (13.52%), Total α-acids (42.58%), and Total ß-acids (26.54%). Once opened, the standard was kept at -18°C in between use.

To prepare the standard extract, it was warmed at 30°C in a water bath and was dissolved in 30 mL of methanol using an ultrasonic bath. The solution was transferred to a 100-mL volumetric flask, and the volume was made up with methanol. After mixing, 10 mL of the solution was pipetted into a 50-mL volumetric flask and made up with methanol. The standard was filtered using a disposable 10 cc/ml syringe (Air-Tite Products Co., Inc., Virginia Beach, Virgina, USA) and a 25 mm, 0.45µm nylon filter (VWR International, LLC, Radnor, Pennsylvania, USA) after mixing. The filtered solution was put into a 1.5-mL amber vial (Agilent, Delaware, USA) and kept at -18°C for up to 24 hours or until injection.

One standard solution sample was introduced into an Agilent Cary 3500 UV-Vis Compact Spectrophotometer (Agilent, Delaware, USA) to determine the best detectable wavelengths for the compounds within the samples. These wavelengths ranged from 233 nm to 352 nm. After analysis and according to previous methods, it was determined that 254 nm detected high absorbance of all target compounds while minimizing noise (Danenhower et al., 2008).

To construct calibration curves, a standard solution was injected three times to assess instrument response and reproducibility. Based on this assessment, concentrations of cohumulone (COH), n- + adhumulone (ADH), colupulone (COL), and n- + adlupulone (ADL) present in the ICE-4 sample (0.5 g) were determined. Seven dilutions were prepared for each compound and injected three times into the HPLC system, and the average peak areas were calculated for each analyte. Calibration curves were then plotted with known concentrations (ppm) on the x-axis and corresponding average peak areas (mAU) on the y-axis, as seen in Figures 3.3 and 3.4 below. Linear regression was applied to each dataset to establish the relationship between concentration and detector response, enabling quantification of these compounds in unknown samples.

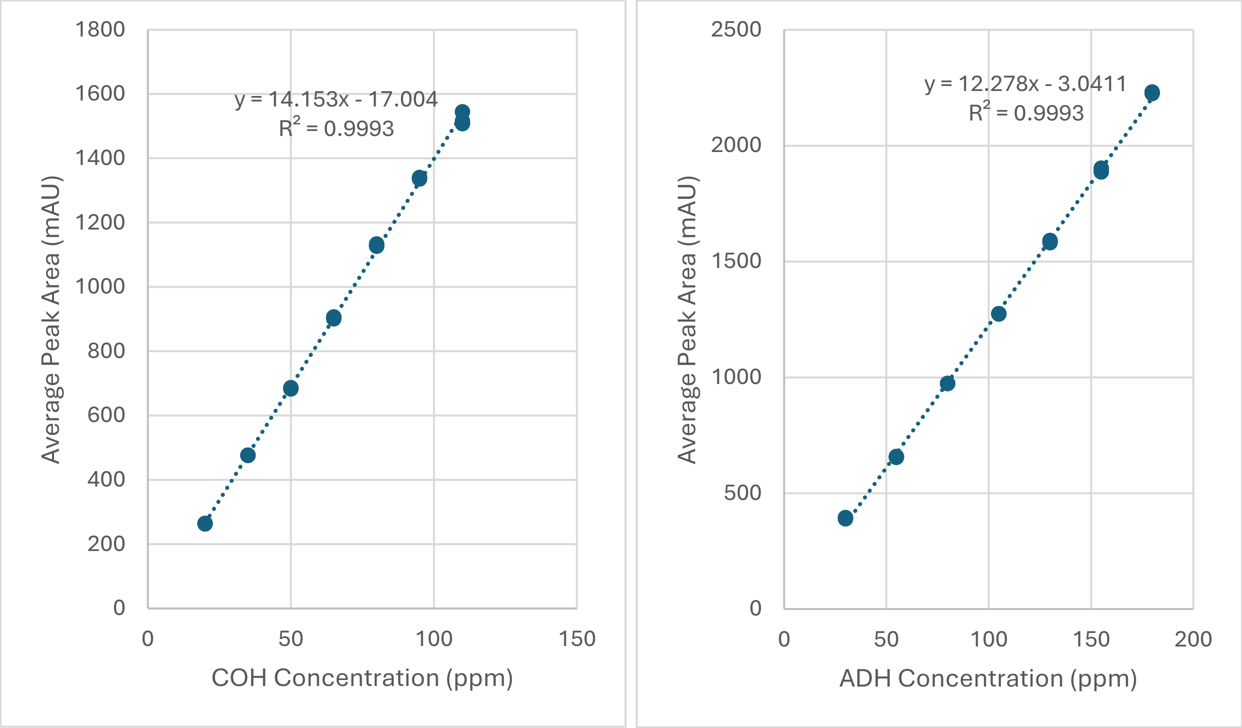

Figure 3.3. Calibration curves for the α-acid components.

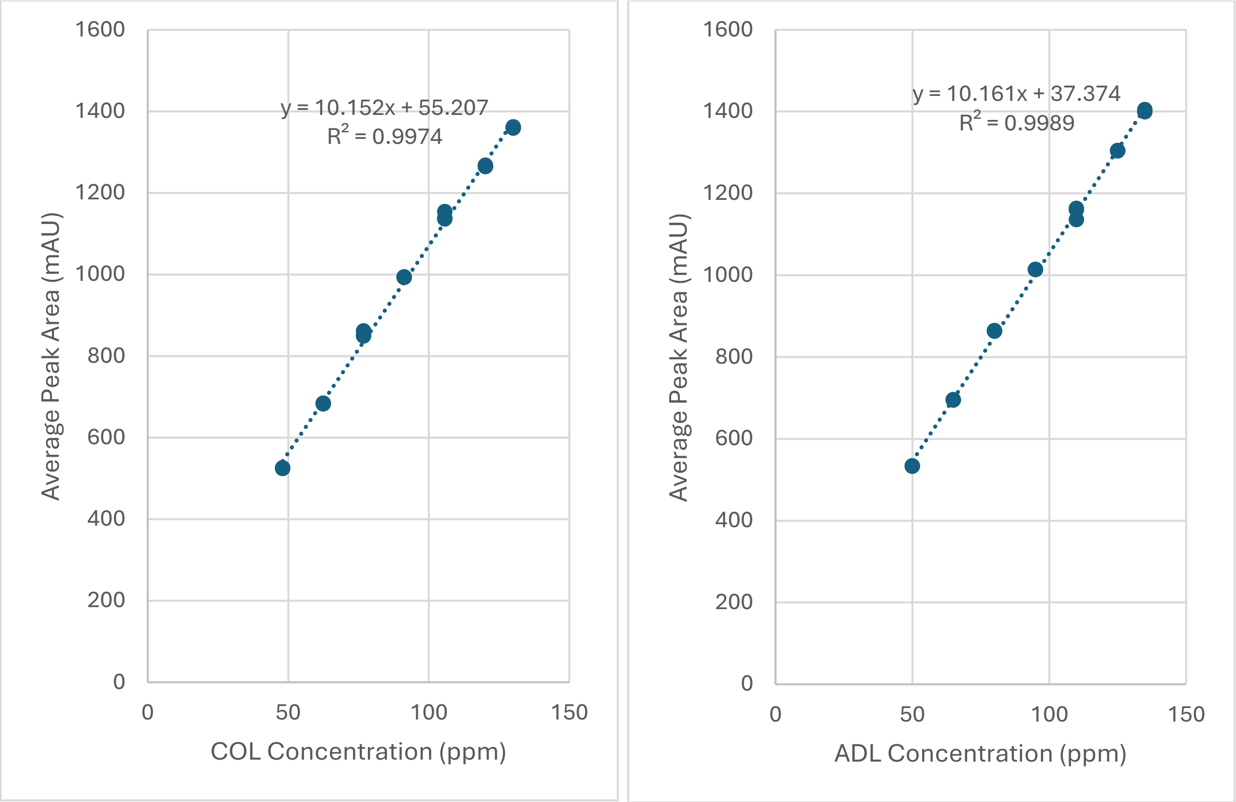

Figure 3.4. Calibration curves for the β-acid components.

Cone samples were ground into a fine powder and weighed to ten grams and 20 mL of HPLC grade methanol and 100 mL of HPLC grade diethyl ether (VWR International, LLC, Radnor, Pennsylvania, USA) were added. A stir bar was placed into each 250-mL extraction bottle, and the solution was allowed to stir for 30 minutes. Then, 40 mL of 0.1*M* hydrochloric acid solution was added (Sigma-Aldrich, St. Louis, Missouri, US) and allowed to stir for ten additional minutes. The bottle was then set to stand for ten minutes to separate the layers. 5.0 mL of the supernatant ether phase was pipetted into a 50-mL volumetric flask, in which the remaining volume was made up with methanol. The solution was mixed and filtered into an amber vial for short-term stock and dilutions were prepared. The solution was assumed to be stable for 24 hours at 18°C.

Test samples were prepared and injected for an indication of the concentrations within the cultivars for each year. The results were used to calculate dilutions of the samples to compare to the calibration curves. The vials of specific dilutions were injected three times each for analysis. Lower concentrations were injected first as to avoid any carryover between vials, and a "blank" vial of only mobile phase solution was injected in between each subplot sample. Additionally, approximately 20% of the samples were repeated on different days of analysis for exploratory data analysis. Table 3.2 shows the dilutions of each cultivar for each year as they were injected. In between each use of the HPLC machine and at the end of all analysis, the machine and column were purged with ultra-pure water to prevent damage.

Table 3.2. Theoretical concentration (ppm) of α– and β-acid compounds and their respective dilution rates (Sample µL:Mobile Phase µL) for cultivars in each year for use in HPLC injections.

		2024		**2025**	
Cultivar	**Compound**	**Theoretical Concentration**	**Dilution Rate**	**Theoretical Concentration**	**Dilution Rate**
'Cascade'	COH[i]	285	250:750	185	500:500
	ADH[ii]	670	250:750	425	250:750
	COL[iii]	215	250:750	131	500:500
	ADL[iv]	269	250:750	124	500:500
'Chinook'	COH	336	200:800	224	250:750
	ADH	1084	100:900	633	167:833
	COL	142	500:500	87	1000:0
	ADL	165	500:500	81	1000:0
'Magnum'	COH	175	333:667	84	1000:0
	ADH	1072	100:900	475	250:750
	COL	89	1000:0	59	1000:0
	ADL	272	1000:0	120	1000:0

[i] COH = Cohumulone
[ii] ADH = Adhumulone
[iii] COL = Colupulone
[iv] ADL = Adlupulone

3.2.7 Hop Tea Preparation for Sensory Evaluation

A tea panel was conducted on October 19, 2024, during the city's Oktoberfest event in Auburn, Alabama. To prepare the hop tea, filtered water was heated to approximately 100 °C. Dried, whole hop cones were added to the heated water, stirred, and steeped for 5 minutes. The mixture was then transferred to a French press for an additional 5-minute steeping period. After brewing, the cones were separated from the liquid using the French press, and the tea was added into water cooler dispensers for serving.

Each batch of hop tea was prepared using one gallon of water per 1.5 cups of dry hop cones. Three dispensers were prepared, each containing a different cultivar (‘Cascade’, ‘Chinook’, or ‘Magnum’). Multiple cone samples were randomly selected from the experimental harvest. No additives, sweeteners, or flavoring agents were used in the preparation. All teas were brewed immediately prior to the event to minimize spoilage and prevent “off flavors” and stored at 4 °C until serving.

To evaluate sensory characteristics, surveys were provided to participants. For each cultivar, tasters were asked to identify any perceived flavors and/or aromas from the following options: citrus, earthy, woody, vanilla, spicy, and/or other.

3.2.8 Statistical Analysis

Field data were analyzed using generalized linear mixed models (GLMM) in RStudio (v.4.4.0; RStudio Team, 2020) to account for non-normality and heteroscedasticity. Fixed effects included trellis type (straight, V), cultivar (‘Cascade’, ‘Chinook’, ‘Magnum’, ‘Neo1’), growth stage (vegetative, flower, cone), year (2024, 2025), and their interactions; plot was treated as a random effect. However, due to missing data for certain factor combinations (i.e., lack of data during the flowering stage and for ‘Neo1’ in 2025), misleading results from interactions not supported in both years were likely, and so a full factorial model across years was not used. Therefore, analyses of photosynthesis rate (A), stomatal conductance (gs), electron transport rate (ETR), and leaf area index (LAI) were conducted separately by year.

Variables with approximately normal and homoscedastic distributions (e.g., height, *A*, Chl, ETR) were modeled using a Gaussian distribution, while strictly positive, skewed, heteroscedastic variables (e.g., LAI, gs) were modeled using a Gamma distribution. When ANOVA indicated significant effects, Tukey's HSD was applied for pairwise comparisons at $\alpha = 0.05$.

For hop cones, calibration curves for HPLC and sensory panel figures were generated in Microsoft Excel (2024). Compound concentrations (COH, ADH, COL, ADL) were analyzed using three-way ANOVA followed by Tukey's test. GLMM with a Gaussian distribution was used for COH and ADH, as well as cone size (homoscedastic data), and a Gamma distribution for COL and ADL, as well as yield (heteroscedastic data), with model selection supported by AIC and residual diagnostics. Plot remained a random effect in all models.

A Mann-Whitney U test and a t-test were used to compare weather variables (rainfall, air temperature, and solar radiation). The Mann-Whitney U test was used to account for skewed, non-normal data (such as rainfall), while the t-test was used to account for mostly normal data, such as temperature.

3.3 Results

In both years, leaf samples were sent to the Auburn University Soil Testing Laboratory to determine any deficiencies, viruses, fungal issues, or presence of mites, as chlorosis and stippling were observed on several plants, in varying severity, with 'Neo1' being most severe (Figure 3.6). All nutrients were sufficient, and viral presence was not detected, but mite cast skins, eggs, and live mites were observed. Leaf necrosis and flower dieback were observed on 'Neo1' at this time, despite a normal report. Bine dieback was also observed for Neo1 during the trellising process (Figure 3.5). The exact cause of these issues is unknown.

Figure 3.5. Bine dieback on 'Neo1' plants.

Figure 3.6. Chlorosis and necrosis on leaves and dieback of flower structures on 'Neo1' plant (left). Moderate stippling from mite damage on 'Neo1' (middle) and 'Cascade' (right).

3.3.1 Environmental Conditions

Peak values for daily air temperatures are in July and August for both years, reaching 36.6°C (98°F) (Figure 3.7). Rainfall accumulation for 2024 was about 940 mm (37 in) (Figure 3.7). Total rainfall was higher in 2025 than in 2024, reaching 1,180 mm (46 in). Relative humidity stayed within the range of about 60 to 95% from the end of April through the end of September. Solar radiation and UV index peaked in June and July, with higher UV index in 2025 (11.7) compared to 2024 (9.5) (*p*-value < 0.05). Photoperiod was consistent for both years, ranging from approximately 11 to 14 hours from February to September, peaking in June.

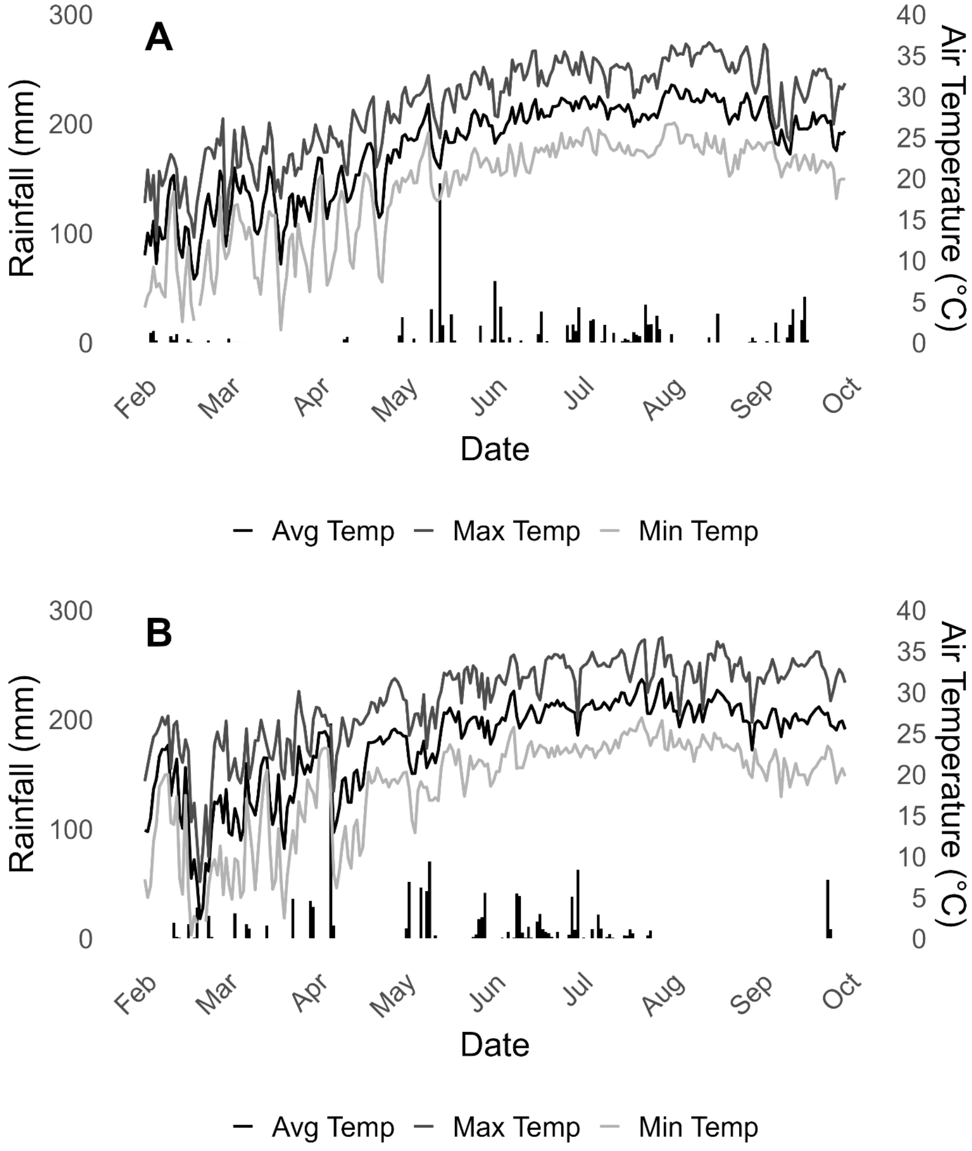

Figure 3.7. Daily weather variation showing minimum (Min Temp), average (Avg Temp), and maximum (Max Temp) air temperatures (°C) and rainfall (mm) from February 1 to October 1 in 2024 (A) and 2025 (B).

[i] 1 mm = 0.0394 in

[ii] °F = (°C * 1.8) +32

3.3.2 Plant Growth, Leaf Area Index, and Biological Efficiencies

Weekly plant height was significantly affected by the two-way interactions between cultivar and growth stage, cultivar and year, and growth stage and year (Table 3.3).

Table 3.3. *p*-values of trellis, cultivar, growth stage, year, and interactions for weekly plant height according to ANOVA test.

	ANOVA *p*-values for Plant Height
Tr[ii]	0.668
Cu[iii]	**0.004**[i]
GS[iv]	**<0.0001**
Yr[v]	**<0.0001**
Tr x Cu	0.687
Tr x GS	0.784
Cu x GS	**0.005**
Tr x Yr	0.828
Cu x Yr	**0.022**
GS x Yr	**<0.0001**
Tr x Cu x GS	0.925
Tr x Cu x Yr	0.880
Tr x GS x Yr	0.978
Cu x GS x Yr	0.533
Tr x Cu x GS x Yr	0.899

[i] *p*-values are significant at $p \leq 0.05$ and in bold.
[ii] Tr = Trellis
[iii] Cu = Cultivar
[iv] GS = Growth stage
[v] Yr = Year

In 2024, ‘Cascade’ was the first cultivar to reach trellis height in week 6, followed by all other hop plants by week 11. In 2025, ‘Chinook’ was the first to reach maximum height (week 8), followed by the other cultivars by week 11 (Figure 3.8).

In both years, plant height in the flowering and cone stages were greatest and not statistically different, indicating rapid bine development in the vegetative stage. It was only during the vegetative stage that cultivars were statistically different, with ‘Cascade’ and ‘Neo1’ exhibiting the greatest height in 2024 (Table 3.4), and ‘Cascade’ and ‘Chinook’ exhibiting the greatest height in 2025 compared to other cultivar treatments (Table 3.5).

Table 3.4. Hop plant height in 2024 across different cultivar treatments and growth stages.

	Plant Height (cm)		
Cultivar	**Vegetative**	**Flower**	**Cone**
‘Cascade’	235.1 ± 20.0[i] a[ii]B[iii]	457.2 ± 24.5 aA	457.2 ± 34.6 aA
‘Chinook’	79.2 ± 20.0 bB	435.2 ± 24.5 aA	457.2 ± 34.6 aA
‘Magnum’	52.5 ± 20.0 bB	381.0 ± 24.5 aA	457.2 ± 34.6 aA
‘Neo1’	191.9 ± 20.0 aB	451.3 ± 24.5 aA	457.2 ± 34.6 aA

[i] Values are represented as mean ± standard error.

[ii] Values followed by similar lowercase letters among cultivars within growth stage indicate no significant difference ($\alpha > 0.05$) according to Tukey’s HSD.

[iii] Values followed by similar uppercase letters among growth stages within cultivar indicate no significant difference ($\alpha > 0.05$) according to Tukey’s HSD.

Table 3.5. Hop plant height in 2025 across different cultivar treatments and growth stages.

	Plant Height (cm)		
Cultivar	**Vegetative**	**Flower**	**Cone**
‘Cascade’	301 ± 32.9[i] a[ii]B[iii]	399 ± 36.8 aA	450 ± 46.5 aA
‘Chinook’	281 ± 32.9 aB	437 ± 36.8 aA	457 ± 46.5 aA
‘Magnum’	186 ± 32.9 bB	407 ± 36.8 aA	457 ± 46.5 aA

[i] Values are represented as mean ± standard error.

[ii] Values followed by similar lowercase letters among cultivars within growth stage indicate no significant difference ($\alpha > 0.05$) according to Tukey’s HSD.

[iii] Values followed by similar uppercase letters among growth stages within cultivar indicate no significant difference ($\alpha > 0.05$) according to Tukey’s HSD.

When comparing plant height between the years, the cultivar ‘Chinook’ grew taller in 2025 compared to the previous year (Table 3.6). Additionally, plants during the vegetative stage of 2025 grew taller overall compared to 2024 (Table 3.7). This indicates that year-to-year differences were most pronounced early in the season and improved growth conditions in the second year.

Table 3.6. Hop plant height among years within cultivar.

	Plant Height (cm)	
Cultivar	**2024**	**2025**
‘Cascade’	346.2 ± 25.3[i] a[ii]	358.7 ± 19.0 a
‘Chinook’	260.9 ± 32.5 b	362.2 ± 24.6 a
‘Magnum’	229.5 ± 32.1 a	304.9 ± 27.2 a

[i] Values are represented as mean ± standard error.

[ii] Values followed by similar uppercase letters among years within a cultivar indicate no significant difference ($\alpha > 0.05$) according to Tukey’s HSD.

Table 3.7. Hop plant height among years within growth stage.

	Plant Height (cm)	
Growth Stage	**2024**	**2025**
Vegetative	139.7 ± 15.7[i] b[ii]	255.9 ± 20.7 a
Flower	431.2 ± 8.2 a	414.4 ± 11.9 a
Cone	457.2 ± 0.0 a	455.0 ± 2.2 a

[i] Values are represented as mean ± standard error.

[ii] Values followed by similar uppercase letters among years within a growth stage indicate no significant difference (α > 0.05) according to Tukey's HSD.

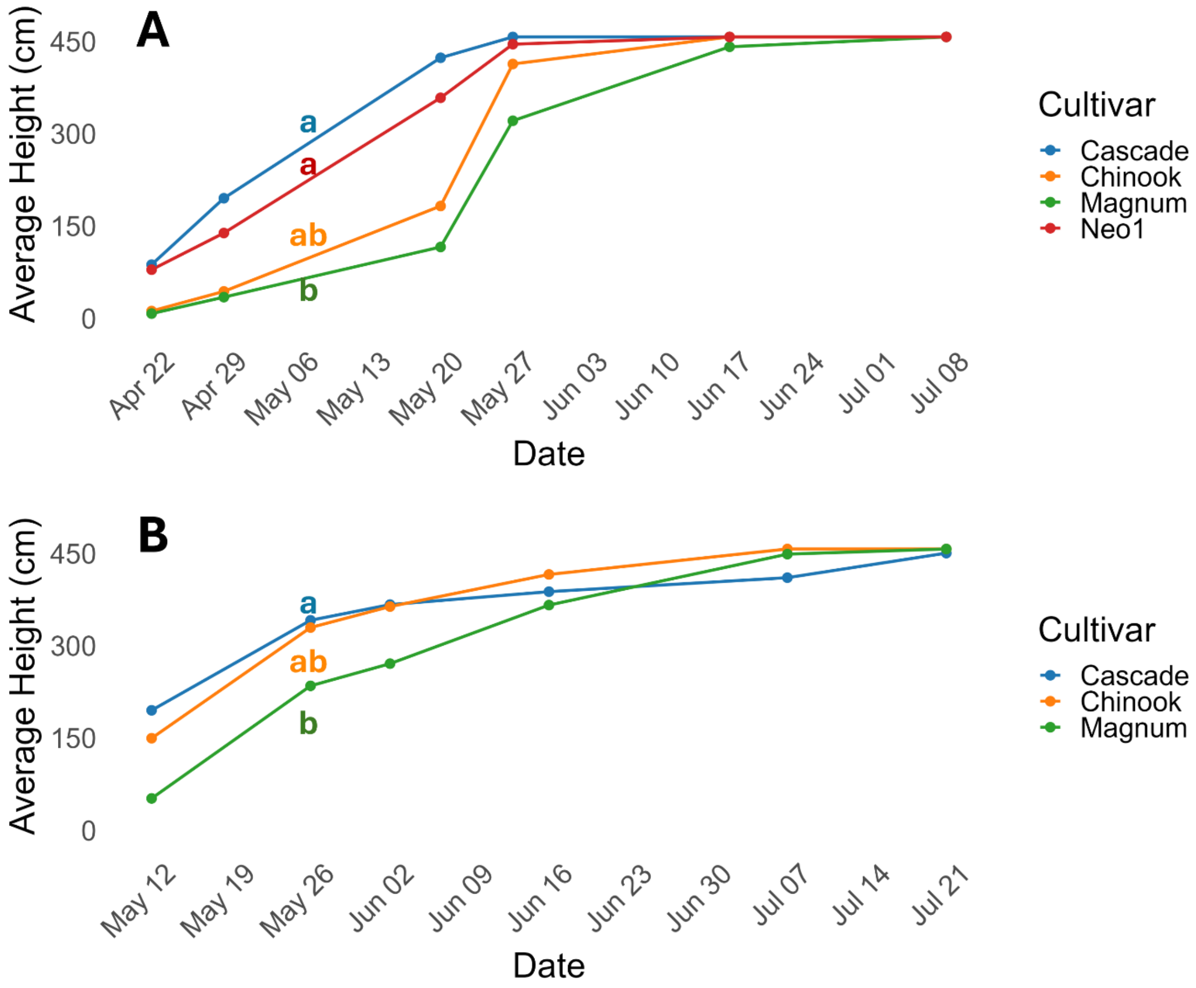

Figure 3.8. Average weekly plant height by cultivar in 2024 (A) and 2025 (B).

[i] Letters indicate statistical differences among cultivars based on Tukey HSD post hoc comparisons. Cultivars sharing the same letter are not significantly different.

[ii] 1 cm = 0.394 in, 0.0328 ft

The main effect of year was found to be significant among all remaining field variables (p-value ≤ 0.05). Table 3.8 shows the p-value results from the ANOVA test for main effects and interactions. In 2024, for photosynthesis rate (A), the interaction between cultivar and growth stage was significant. For stomatal conductance (gs), the two-way interactions between trellis and cultivar, and cultivar and growth stage were significant. The interaction between cultivar and growth stage was also significant for electron transport rate (ETR). All interactions were significant for chlorophyll index (Chl). Only the main effect of growth stage was significant for leaf area index (LAI).

The main effect of growth stage was significant for A, gs, ETR, and Chl in 2025. Additionally, the other main effects (trellis and cultivar) were also significant for Chl. The interaction between trellis and growth stage was significant for LAI in 2025.

Table 3.8. p-values of trellis, cultivar, growth stage, and interactions for 2024 and 2025 across A, gs, and ETR according to ANOVA test.

		ANOVA *p*-values				
		A[v]	**gs**[vi]	**ETR**[vii]	**Chl**[viii]	**LAI**[ix]
2024	**Tr**[ii]	0.858	0.086	0.106	**0.001**	0.972
	Cu[iii]	**0.007**[i]	**<0.0001**	0.783	**<0.0001**	**0.052**
	GS[iv]	**0.015**	**0.004**	**0.000**	**<0.0001**	**<0.0001**
	Tr x Cu	0.669	**0.024**	0.499	**0.002**	0.063
	Tr x GS	0.875	0.097	0.342	**0.001**	0.498
	Cu x GS	**0.009**	**0.017**	**0.019**	**0.001**	0.075
	Tr x Cu x GS	0.253	0.207	0.466	**0.005**	0.109
2025	**Tr**	0.972	0.345	0.651	**0.019**	**0.015**
	Cu	0.556	0.843	0.838	**0.047**	0.391
	GS	**<0.0001**	**0.049**	**<0.0001**	**0.354**	0.201
	Tr x Cu	0.408	nan[x]	nan	0.574	0.242
	Tr x GS	0.476	nan	nan	0.305	**0.009**
	Cu x GS	0.828	nan	nan	0.895	0.080
	Tr x Cu x GS	0.717	nan	nan	0.996	0.082

[i] p-values are significant at $p \le 0.05$ and in bold.
[ii] Tr = Trellis.
[iii] Cu = Cultivar.
[iv] GS = Growth stage.
[v] A = Photosynthesis rate.

[vi] gs = Stomatal conductance.
[vii] ETR = Electron transport rate.
[viii] Chl = Chlorophyll index.
[ix] LAI = Leaf area index.
[x] "nan" indicates combinations not evaluated in 2025 due to missing or invalid data.

In 2024 (Table 3.9), *A* was significantly lower in the cone stage. During the vegetative and flower stages, *A* was similar and consistent among cultivars, except for 'Magnum', which went from highest values in the vegetative stage (20.6 ± 1.5 µmol CO_2 m^{-2} s^{-1}) to intermediate values in the flower stage (14.4 ± 1.5 µmol CO_2 m^{-2} s^{-1}). Within each growth stage, however, there was not any significant difference among the cultivars.

In 2025 (Table 3.10), *A* was highest in the vegetative stage (29.4 ± 1.6 µmol CO_2 m^{-2} s^{-1}) and lowest in the cone stage (4.2 ± 1.8 µmol CO_2 m^{-2} s^{-1}).

Table 3.9. Photosynthesis rate (*A*) of hops in 2024 across different cultivar treatments and growth stages.

	Photosynthesis rate, *A* (µmol CO_2 m^{-2} s^{-1})		
Cultivar	**Vegetative**	**Flower**	**Cone**
'Cascade'	19.2 ± 1.5[i] ab[ii]	17.1 ± 1.5 ab	11.1 ± 1.5 b
'Chinook'	21.4 ± 1.5 ab	16.5 ± 1.5 ab	8.4 ± 1.5 b
'Magnum'	20.6 ± 1.5 a	14.4 ± 1.5 ab	7.6 ± 1.5 b
'Neo1'	16.2 ± 1.5 ab	18.6 ± 1.5 ab	5.5 ± 1.7 b

[i] Values are represented as mean ± standard error.
[ii] Values followed by similar lowercase letters among growth stages within cultivar indicate no significant difference ($\alpha > 0.05$) according to Tukey's HSD.

Table 3.10. Average photosynthesis rate (*A*) of hops in 2025 across different growth stages.

Photosynthesis rate, *A* (µmol CO_2 m^{-2} s^{-1})	
Vegetative	**Cone**
29.4 ± 1.6[i] a[ii]	4.2 ± 1.8 b

[i] Values are represented as mean ± standard error.
[ii] Values followed by similar lowercase letters among growth stage indicate no significant difference ($\alpha > 0.05$) according to Tukey's HSD.

In 2024, gs was highest for most cultivars in the vegetative and flower stages and dropped off in the cone stage. 'Cascade', however, had no variation among growth stages and stayed consistent from vegetative growth to reproduction. Additionally, across all growth stages, ‘Neo1’ exhibited the lowest gs, with other cultivars being statistically the same, except for ‘Magnum’ on the V-trellis, which demonstrated intermediate gs (Table 3.11).

In 2025, gs during the vegetative stage (0.3 ± 0.0 mol H_2O m^{-2} s^{-1}) was significantly higher than in the cone stage (0.2 ± 0.0 mol H_2O m^{-2} s^{-1}), a similar trend to 2024 (Table 3.12)

Table 3.11. Stomatal conductance (gs) of hops in 2024 across different treatments and growth stages.

		Stomatal conductance, gs (mol H_2O m^{-2} s^{-1})		
Trellis	**Cultivar**	**Vegetative**	**Flower**	**Cone**
Straight	‘Cascade’	0.7 ± 0.0[i] a[ii]B[iii]	1.1 ± 0.5 aB	0.4 ± 0.1 aB
	‘Chinook’	0.7 ± 0.1 aA	1.4 ± 0.5 aA	0.4 ± 0.1 aB
	‘Magnum’	0.8 ± 0.1 aA	1.1 ± 0.2 aA	0.4 ± 0.1 aB
	‘Neo1’	0.5 ± 0.0 bA	0.8 ± 0.1 bA	0.1 ± 0.0 bB
V	‘Cascade’	0.7 ± 0.0 aB	0.7 ± 0.4 aB	0.7 ± 0.3 aB
	‘Chinook’	0.9 ± 0.1 aA	1.0 ± 0.2 aA	0.2 ± 0.0 aB
	‘Magnum’	0.6 ± 0.1 abA	0.7 ± 0.1 abA	0.2 ± 0.1 abB
	‘Neo1’	0.4 ± 0.1 bA	0.4 ± 0.1 bA	0.1 ± 0.0 bB

[i] Values are represented as mean ± standard error.

[ii] Values followed by similar lowercase letters among treatments (cultivar and trellis) indicate no significant difference (α > 0.05) according to Tukey’s HSD.

[iii] Values followed by similar uppercase letters among growth stages and cultivars indicate no significant difference (α > 0.05) according to Tukey’s HSD.

Table 3.12. Average stomatal conductance (gs) of hops in 2025 across different growth stages.

Stomatal conductance, gs (mol H_2O m^{-2} s^{-1})	
Vegetative	**Cone**
0.3 ± 0.0[i] a[ii]	0.2 ± 0.0 b

[i] Values are represented as mean ± standard error.

[ii] Values followed by similar lowercase letters among growth stage indicate no significant difference (α > 0.05) according to Tukey’s HSD.

In 2024, ETR was highest in the vegetative stage for all cultivars and lowest in the cone stage, and cultivars were statistically similar during these times (Table 3.13). During the flower stage, ETR for ‘Cascade’ and ‘Neo1’ was similar to that of the vegetative stage, indicating continued, strong photosynthetic activity. Additionally, ‘Neo1’ had the highest ETR during flowering (135.9 ± 10.4 m^{-2} s^{-1}), followed by 'Magnum' (81.8 ± 10.4 m^{-2} s^{-1}), then 'Cascade' and 'Chinook' (103.7 ± 10.4 and 93.3 ± 10.4 m^{-2} s^{-1}, respectively).

In 2025, the vegetative stage (172.7 ± 8.2 m^{-2} s^{-1}) had significantly higher ETR than the cone stage (39.04 ± 9.9 m^{-2} s^{-1}), indicating a strong decline in photosynthetic activity during reproduction (Table 3.14).

Table 3.13. Electron transport rate (ETR) of hops in 2024 across different cultivar treatments and growth stages.

	Electron transport rate, ETR (m^{-2} s^{-1})		
Cultivar	**Vegetative**	**Flower**	**Cone**
'Cascade'	120.2 ± 10.4[i] b[ii]A[iii]	103.7 ± 10.4 bA	66.3 ± 10.4 bB
'Chinook'	137 ± 10.4 bA	93.3 ± 10.4 bB	67.4 ± 10.4 bB
'Magnum'	126 ± 10.4 bA	81.8 ± 10.4 abB	50.7 ± 10.4 bB
'Neo1'	109.8 ± 10.4 bA	135.9 ± 10.4 aA	69.3 ± 10.4 bB

[i] Values are represented as mean ± standard error.

[ii] Values followed by similar lowercase letters among cultivar within growth stage indicate no significant difference ($\alpha > 0.05$) according to Tukey's HSD.

[iii] Values followed by similar uppercase letters among growth stages within cultivar indicate no significant difference ($\alpha > 0.05$) according to Tukey's HSD.

Table 3.14. Average electron transport rate (ETR) of hops in 2025 across different growth stages.

Electron transport rate, ETR (m^{-2} s^{-1})	
Vegetative	**Cone**
172.7 ± 8.2[i] a[ii]	39.04 ± 9.9 b

[i] Values are represented as mean ± standard error.

[ii] Values followed by similar lowercase letters among growth stage indicate no significant difference ($\alpha > 0.05$) according to Tukey's HSD.

In 2024, Tukey's HSD revealed no differences in treatments in the vegetative stage for chlorophyll index (Chl) (Table 3.15). This remained true in the flower stage, except for 'Neo1' on the V-trellis (39.5 ± 2.4 μg/cm^2), in which Chl was significantly higher than other trellis treatments within cultivar (Table 3.16). During the cone stage, Chl was significantly higher for 'Cascade' on the straight trellis (39.9 ± 2.4 μg/cm^2) compared to the V-trellis (30.7 ± 2.4 μg/cm^2), while other cultivars showed no trellis-related differences. Among the cultivars on the straight trellis, 'Cascade' had the highest Chl. There were no differences among cultivars on the V-trellis (Table 3.17). When comparing overall Chl among growth stages (Table 3.18), values were lowest during the vegetative stage (22.7 ± 0.8 µg/cm^2). There were no differences between the flowering and cone stages (33.5 ± 0.8 and 30.6 ± 0.8 µg/cm^2, respectively).

Table 3.15. Chlorophyl index (Chl) of hops in 2024 across different treatments in the vegetative stage.

	Chlorophyll index, Chl (µg/cm^2) at Vegetative	
Cultivar	**Straight trellis**	**V-trellis**
'Cascade'	22.4 ± 2.4[i]	23.5 ± 2.4
'Chinook'	25.2 ± 2.4	23.8 ± 2.4
'Magnum'	22.0 ± 2.4	22.4 ± 2.4
'Neo1'	22.3 ± 2.4	20.1 ± 2.4

[i] Values are represented as mean ± standard error.

Table 3.16. Chlorophyll index (Chl) of hops in 2024 across different treatments in the flower sta ge.

	Chlorophyll index, Chl (µg/cm^2) at Flower	
Cultivar	**Straight trellis**	**V-trellis**
'Cascade'	30.8 ± 2.4[i]	35.6 ± 2.4
'Chinook'	35.5 ± 2.4	30.8 ± 2.4
'Magnum'	33.5 ± 2.4	33.5 ± 2.4
'Neo1'	29.1 ± 2.4	39.5 ± 2.4 a[ii]

[i] Values are represented as mean ± standard error.

[ii] Values followed by lowercase letters among trellis within cultivar indicate a significant difference (α > 0.05) according to Tukey's HSD.

Table 3.17. Chlorophyll index (Chl) of hops in 2024 across different treatments in the cone stage .

	Chlorophyll index, Chl (µg/cm^2) at Cone	
Cultivar	**Straight trellis**	**V-trellis**
'Cascade'	39.9 ± 2.4[i] a[ii]A[iii]	30.7 ± 2.4 bB
'Chinook'	32.9 ± 2.4 bAB	29.0 ± 2.4 bB
'Magnum'	30.7 ± 2.4 bB	27.7 ± 2.4 bB
'Neo1'	24.4 ± 2.4 bB	29.9 ± 2.4 bB

[i] Values are represented as mean ± standard error.

[ii] Values followed by similar lowercase letters among trellis within cultivar indicate no significant difference (α > 0.05) according to Tukey's HSD.

[iii] Values followed by similar uppercase letters among cultivar within trellis indicate no significant difference (α > 0.05) according to Tukey's HSD.

Table 3.18. Average chlorophyll index (Chl) of hops in 2024 across growth stages.

Growth stage	**Chlorophyll index, Chl (µg/cm^2)**
Vegetative	22.7 ± 0.8[i] b[ii]
Flower	33.5 ± 0.8 a
Cone	30.6 ± 0.8 a

[i] Values are represented as mean ± standard error.

[ii] Values followed by similar lowercase letters among growth stage indicate no significant difference ($\alpha > 0.05$) according to Tukey's HSD.

In 2025, Chl was highest for the cultivar 'Cascade' (27.9 ± 1.2 µg/cm^2), intermediate for 'Chinook' (25.5 ± 1.1 µg/cm^2), and lowest for 'Magnum' (22.2 ± 1.1 µg/cm^2) (Table 3.19). Additionally, overall Chl on the straight trellis was significantly higher than that of the V-trellis (27.1 ± 1.0 and 23.3 ± 0.9 1 µg/cm^2, respectively) (Table 3.20). Although growth stage was significant according to the ANOVA, Tukey's HSD pairwise comparisons indicated no significant difference between the cone and vegetative stages.

Table 3.19. Average chlorophyll index (Chl) of hops in 2025 across cultivar.

Cultivar	**Chlorophyll index, Chl (µg/cm^2)**
'Cascade'	27.9 ± 1.2[i] a[ii]
'Chinook'	25.5 ± 1.1 ab
'Magnum'	22.2 ± 1.1 b

[i] Values are represented as mean ± standard error.

[ii] Values followed by similar lowercase letters among cultivar indicate no significant difference ($\alpha > 0.05$) according to Tukey's HSD.

Table 3.20. Average chlorophyll index (Chl) of hops in 2025 across trellis system.

Trellis	**Chlorophyll index, Chl (µg/cm^2)**
Straight	27.1 ± 1.0[i] a[ii]
V	23.3 ± 0.9 b

[i] Values are represented as mean ± standard error.

[ii] Values followed by similar lowercase letters among trellis indicate no significant difference ($\alpha > 0.05$) according to Tukey's HSD.

'Cascade' consistently had the greatest biomass accumulation in both years over time, followed by 'Chinook' and 'Neo1', then 'Magnum'. 'Neo1' experienced severe foliage and cone loss before harvest, which may not be fully reflected in these LAI measurements. In 2025, maximum potential of LAI may not have been achieved by harvest, as seen in Figure 3.9.

In 2024 (Table 3.21), LAI was highest during the flowering stage (1.1 ± 0.1 m^2/m^2) and dropped off in the cone stage (0.5 ± 0.1 m^2/m^2), possibly due to overcast conditions and/or loss of foliage in ‘Neo1’. Additionally, ‘Cascade’ in 2024 had the highest LAI compared to other cultivars (Table3.22). In 2025 (Table 3.23), trellis within growth stage had no significant effect on LAI. LAI, however, was higher in the cone stage than the vegetative stage during this year.

Table 3.21. Leaf area index (LAI) of hops in 2024 across different growth stages.

Leaf area index, LAI (m^2/m^2)		
Vegetative	**Flower**	**Cone**
0.2 ± 0.0[i] b[ii]	1.1 ± 0.1 a	0.5 ± 0.1 ab

[i] Values are represented as mean ± standard error.

[ii] Values followed by similar lowercase letters among growth stage indicate no significant difference ($\alpha > 0.05$) according to Tukey’s HSD.

Table 3.22. Leaf area index (LAI) of hops in 2024 across different cultivars.

Cultivar	**Leaf area index, LAI (m^2/m^2)**
‘Cascade’	0.8 ± 0.1[i] a[ii]
‘Chinook’	0.5 ± 0.1 b
‘Magnum’	0.4 ± 0.0 b
‘Neo1’	0.4 ± 0.1 b

[i] Values are represented as mean ± standard error.

[ii] Values followed by similar lowercase letters among cultivar indicate no significant difference ($\alpha > 0.05$) according to Tukey’s HSD.

Table 3.23. Leaf area index (LAI) of hops in 2025 across trellis and growth stages.

	Leaf area index, LAI (m^2/m^2)	
Trellis	**Vegetative**	**Cone**
Straight	0.2 ± 0.0[i] b[ii]	0.6 ± 0.1 a
V	0.3 ± 0.0 b	1.0 ± 0.2 a

[i] Values are represented as mean ± standard error.

[ii] Values followed by similar lowercase letters among growth stage within trellis indicate no significant difference ($\alpha > 0.05$) according to Tukey’s HSD.

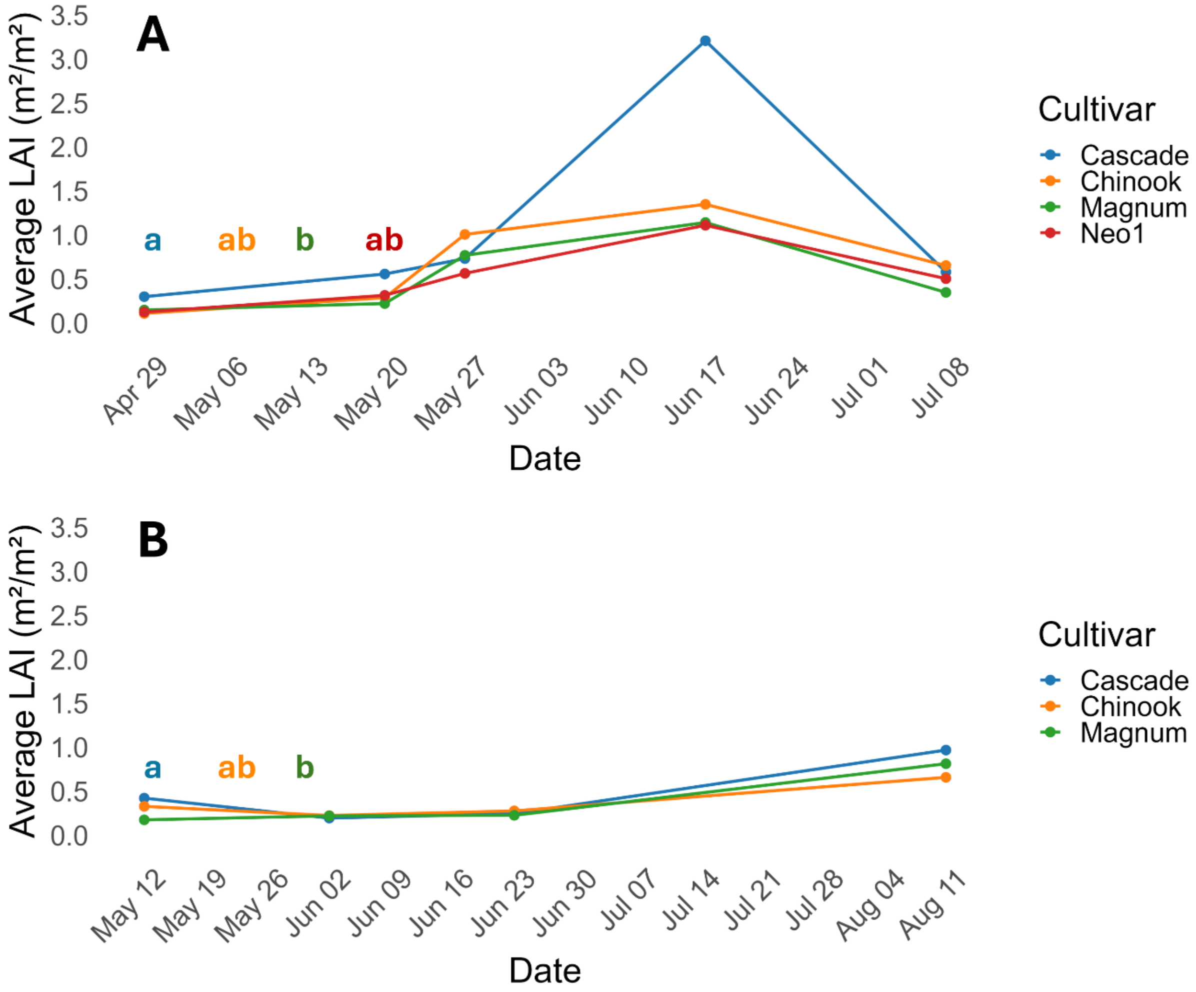

Figure 3.9. Average weekly LAI (m^2/m^2) by cultivar in 2024 (A) and 2025 (B).

[i] Letters indicate statistical differences among cultivars based on Tukey HSD post hoc comparisons. Cultivars sharing the same letter are not significantly different.

[ii] Late-stage data collections for 2024 were overcast days, likely contributing to the decline of LAI due to poorer readings.

Figures 3.10 and 3.11 visualize the biomass accumulation via drone imaging from early May and mid-June of 2024, during the vegetative and cone stages of the plants, respectively. A significant increase in plant matter can be seen in both the orthomosaic and infrared images.

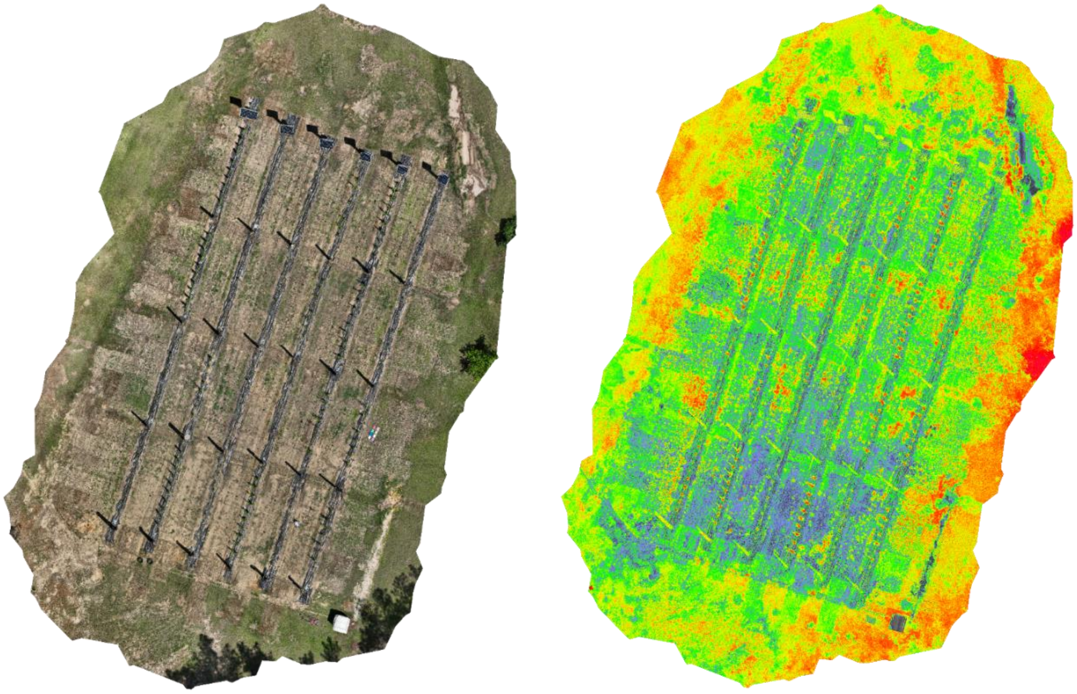

Figure 3.10. Visualization of biomass via drone imagine in early May 2024 during the vegetative stage.

[i] In the rows from left to right, trellis types are: straight, straight, V, V, V, straight

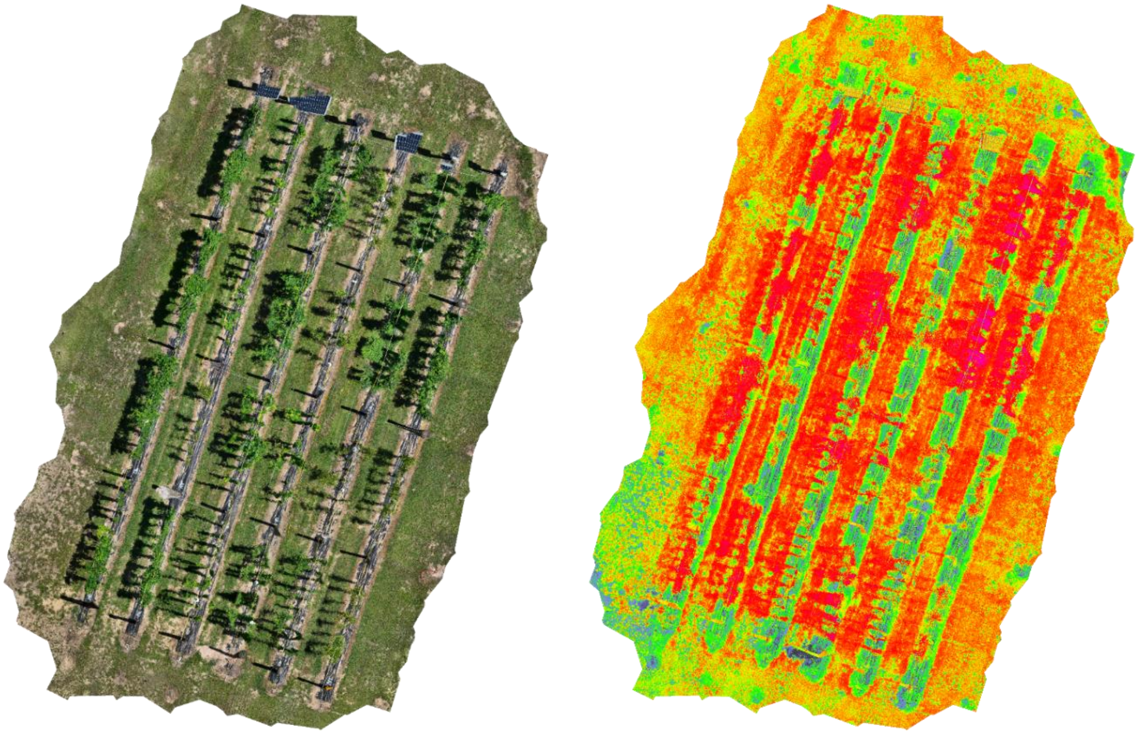

Figure 3.11. Visualization of biomass via drone imaging in mid-June during the cone stage.

[i] In the rows from left to right, trellis types are: straight, straight, V, V, V, straight

3.3.3 Yield and Cone Size

For yield, the two-way interaction between cultivar and yield was found to be significant according to ANOVA testing (Table 3.24). Cone width was significant for the two-way interaction between cultivar and year, and the three-way interaction between trellis, cultivar, and year. For cone length, only the main effect of cultivar was significant.

Table 3.24. *p*-values of trellis, cultivar, year, and interactions across yield and cone size according to ANOVA test.

	ANOVA *p*-values for Yield and Cone Size			
	FCY[ii]	**DCY**[iii]	**Width**	**Length**
Tr[iv]	0.081	0.093	0.121	0.144
Cu[v]	**0.042**[i]	**0.051**	**<0.0001**	**0.005**
Yr[vi]	**<0.0001**	**<0.0001**	**<0.0001**	0.358
Tr x Cu	0.119	0.141	0.107	0.089
Tr x Yr	0.087	0.094	0.170	0.183
Cu x Yr	**0.044**	**0.052**	**0.040**	0.284
Tr x Cu x Yr	0.132	0.149	**0.0146**	0.2159

[i] *p*-values are significant at $p \leq 0.05$ and in bold.
[ii] FCY = Fresh cone yield.
[iii] DCY = Dry cone yield.
[iv] Tr = Trellis.
[v] Cu = Cultivar.
[vi] GS = Growth stage.
[vii] Yr = Year.

In 2024, fresh cone yield (FCY) for ‘Cascade’ and ‘Chinook’ were similar and significantly higher (2,787 ± 755.2 and 2,324.1 ± 629.8 kg ha^{-1}, respectively) than ‘Magnum’ (671.4 ± 181.9 kg ha^{-1}). Similarly, ‘Cascade’ and ‘Chinook’ had the highest FCY again (573.7 ± 155.5 and 942.2 ± 255.3 kg ha^{-1}, respectively) in 2025 compared to ‘Magnum’ (160.8 ± 46.9 kg ha^{-1}). When comparing the two years, yields overall dropped significantly from 2024 to 2025. This trend continued for dry cone yield (DCY) (Table 3.25). Trellis was not a significant factor in cone yield.

Table 3.25. Fresh and dry cone yields of hops in 2024 and 2025 under different cultivar treatments.

Cultivar	**FCY[i] (kg ha-1)**	
	2024	**2025**
'Cascade'	2,787 ± 755.2[ii] a[iii]	573.7 ± 155.5 a
'Chinook'	2,324.1 ± 629.8 a	942.2 ± 255.3 a
'Magnum'	671.4 ± 181.9 b	160.8 ± 46.9 b
Average of Treatments	2,160.1 ± 368.6 A[iv]	720 ± 150.6 B
Cultivar	**DCY[v] (kg ha-1)**	
	2024	**2025**
'Cascade'	791.3 ± 204.9 a	90.4 ± 23.4 a
'Chinook'	588.7 ± 152.4 a	110.2 ± 28.5 a
'Magnum'	190.5 ± 49.3 b	23.7 ± 6.5 b
Average of Treatments	597 ± 106.1 A	94.2 ± 17.6 B

[i] FCY: fresh cone yield.

[ii] Values are presented as mean ± standard error.

[iii] Values followed by similar lowercase letters among cultivars within year indicate no significant difference ($p > 0.05$) according to Tukey's test.

[iv] Values followed by similar uppercase letters among years indicate no significant difference ($p > 0.05$) according to Tukey's test.

[v] DCY: dry cone yield.

Trellis and year were not significant factors when it came to hop cone length. 'Chinook' had the longest cones (2.5 ± 0.1 cm), while 'Cascade' had intermediate lengths (2.1 ± 0.1 cm) and 'Magnum' had the shortest cones of all cultivars (1.9 ± 0.1 cm) (Table 3.26).

Regarding hop cone width, 'Chinook' consistently had the widest cones in both years (1.9 ± 0.1 cm in 2024 and 2.4 ± 0.1 in 2025) compared to the other cultivars. 'Chinook' and 'Magnum' showed an increase in cone width from the first to the second year, and 'Cascade' remained stable (Table 3.27). Additionally, in 2024, 'Cascade' on the straight trellis exhibited wider cones (1.9 ± 0.1 cm) than on the V-trellis (1.4 ± 0.1 cm). When comparing years within treatments, 'Chinook' cones on the straight trellis increased in width from 2024 to 2025. On the V-trellis, 'Cascade' and 'Chinook' also had an increase in width (Table 3.28).

Table 3.26. Hop cone length across cultivars.

Cultivar	Cone Length (cm)
'Cascade'	2.1 ± 0.1[i] ab[ii]
'Chinook'	2.5 ± 0.1 a
'Magnum'	1.9 ± 0.1 b

[i] Values are represented as mean ± standard error.

[ii] Values followed by similar lowercase letters among cultivars indicate no significant difference (α > 0.05) according to Tukey's HSD.

Table 3.27. Hop cone width across cultivars and years.

	Cone Width (cm)	
Cultivar	**2024**	**2025**
'Cascade'	1.6 ± 0.1 bB	1.7 ± 0.1 bB
'Chinook'	1.9 ± 0.1 aB	2.4 ± 0.1 aA
'Magnum'	1.7 ± 0.1 bB	1.9 ± 0.1 bA

[i] Values are represented as mean ± standard error.

[ii] Values followed by similar lowercase letters among cultivars within year indicate no significant difference (α > 0.05) according to Tukey's HSD.

[iii] Values followed by similar uppercase letters among years within cultivar indicate no significant difference (α > 0.05) according to Tukey's HSD.

Table 3.28. Hop cone width across treatments and years.

		Cone Width (cm)	
Trellis	**Cultivar**	**2024**	**2025**
Straight	**'Cascade'**	1.9 ± 0.1 aB	1.7 ± 0.1 bB
	'Chinook'	1.9 ± 0.1 aB	2.4 ± 0.1 aA
	'Magnum'	1.7 ± 0.1 abB	1.9 ± 0.1 bB
V	**'Cascade'**	1.4 ± 0.1 bB	1.8 ± 0.1 bA
	'Chinook'	2.0 ± 0.1 aB	2.3 ± 0.1 aA
	'Magnum'	1.7 ± 0.1 abA	1.9 ± 0.1 bA

[i] Values are represented as mean ± standard error.

[ii] Values followed by similar lowercase letters among trellis and cultivar within year indicate no significant difference (α > 0.05) according to Tukey's HSD.

[iii] Values followed by similar uppercase letters among years within cultivar and trellis indicate no significant difference (α > 0.05) according to Tukey's HSD.

3.3.4 Cone Quality

A total of 37 participants provided responses for Chinook samples, 20 for Cascade, and 24 for Magnum during the 2024 tea panel. Contributors included enthusiasts, growers, and brewers.

As visualized in Figure 3.12, Chinook cones were perceived as having a mostly spicy (31.9%) and woody (26.4%) flavor, with a more complex citrus (27.0%), spicy (23.8%), earthy (22.2%), and woody aroma (22.2%). Brewers and enthusiasts most often reported woody and spicy flavors, while growers additionally noted the citrus flavors. All participants recognized a variety of aromas, with growers having a high response for a citrus aroma, especially.

For the cultivar Cascade (Figure 3.13), earthy (37.8%) and woody (32.4%) flavors and aromas (35.3% woody, 32.4% earthy) were reported. Brewers mostly had a perception of the earthy flavor and aroma, but a large response for vanilla aroma, as well. Growers and enthusiasts had similar perceptions of both aroma and flavor, although growers noted a citrus aroma, and enthusiasts a vanilla aroma, more often.

Finally, Magnum (Figure 3.14) was mostly described as having an earthy flavor and aroma (32.5% and 24.4% respectively), and/or a woody flavor and aroma (32.5% and 34.1% respectively). Growers had the highest perception of the earthy flavor and woody aroma. Overall, the perception of aroma for Magnum was highly variable.

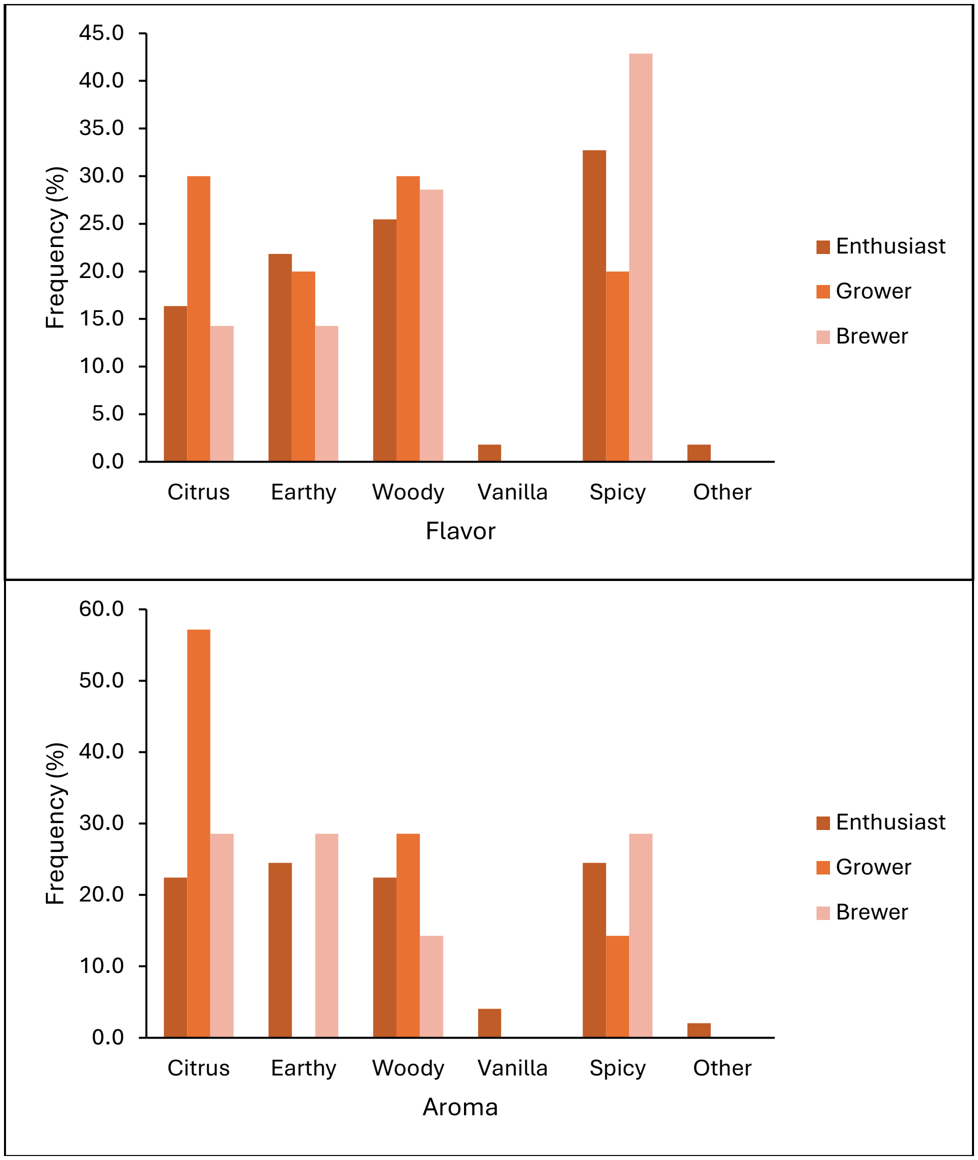

Figure 3.12. Public perception of flavor and aroma for the cultivar ‘Chinook’.
[i] Other aroma includes “jasmine” and other flavor includes “tropical”.

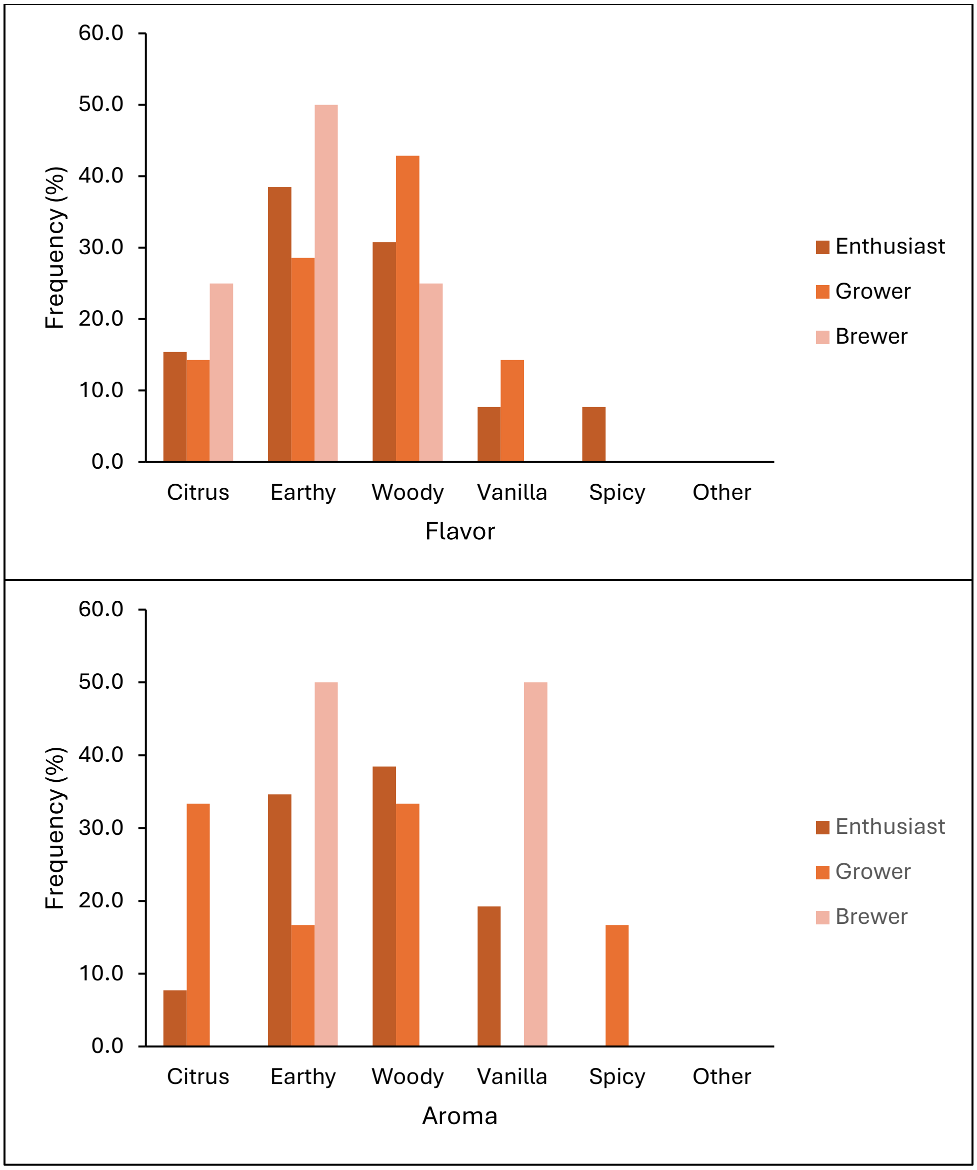

Figure 3.13. Public perception of flavor and aroma for the cultivar ‘Cascade’.

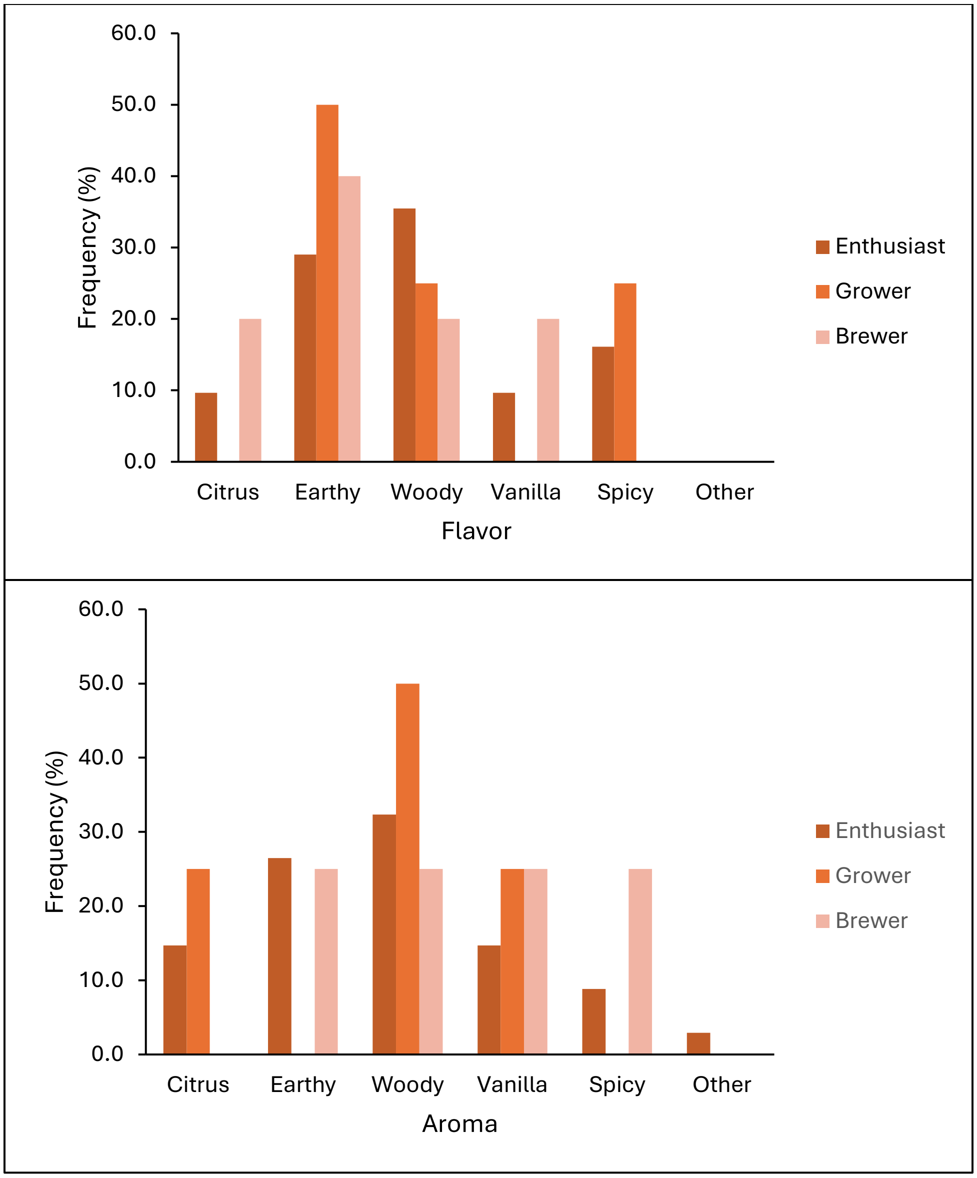

Figure 3.14. Public perception of flavor and aroma for the cultivar ‘Magnum’.
[i] Other aroma includes “green tea”.

All α– and β-acid components were found to be significant for the three-way interaction between trellis, cultivar, and year (Table 3.29). Additionally, the two-way interaction between cultivar and trellis was significant for the component adhumulone (ADH), and the two-way interaction between trellis and cultivar for colupulone (COL). Total α- and β-acid content across cultivars and years can be seen in Figure 3.15.

Table 3.29. *p*-values and statistical significance of trellis, cultivar, year, and interactions across α− and β-acid compounds according to ANOVA test.

	α-acids (%)		**β-acids (%)**	
	COH[ii]	**ADH[iii]**	**COL[iv]**	**ADL[v]**
Tr[vi]	0.130	**0.013**	**0.010**	**0.041**
Cu[vii]	**<0.0001**[i]	**0.004**	**<0.0001**	**<0.0001**
Yr[viii]	**0.002**	**<0.0001**	0.180	**0.008**
Tr x Cu	0.531	0.535	0.313	0.332
Tr x Yr	0.604	0.383	**0.016**	0.154
Cu x Yr	0.0614	**0.000**	0.249	0.428
Tr x Cu x Yr	**0.014**	**0.001**	**0.002**	**<0.0001**

[i] *p*-values are significant at $p \leq 0.05$ and in bold.
[ii] COH = Cohumulone.
[iii] ADH = Adhumulone.
[iv] COL = Colupulone.
[v] ADH = Adlupulone.
[vi] Tr = Trellis.
[vii] Cu = Cultivar.
[viii] Yr = Year.

For cohumulone (COH) in 2024, ‘Chinook’ had the highest concentration on the straight trellis (3.1 ± 0.2 %), followed by ‘Cascade’ on the same trellis (2.8 ± 0.3 %) and ‘Chinook’ on the V-trellis (2.7 ± 0.3 %), which were not statistically different. ‘Magnum’ on either trellis systems had the lowest COH (about 1.5 – 1.9 %).

In 2025, ‘Chinook’ and ‘Cascade’ had the highest COH (2.5 ± 0.2 % and 2.2 ± 0.3 %) on the straight trellis and V-trellis, respectively. Intermediate COH concentration was found in ‘Chinook’ and ‘Cascade’, again, on the V-trellis (2.2 ± 0.3 %) and straight trellis (2.2 ± 0.3 %), respectively. Like 2024, ‘Magnum’, again, had the lowest COH of about 0.8 – 1.2 %.

When comparing the two years, ‘Chinook’ (straight trellis) and ‘Magnum’ (V-trellis) had a decrease in COH from 2024 to 2025, while other treatment combinations remained stable (Table 3.30). Overall, ‘Chinook’ had the highest COH concentration, especially in 2024, and the effect of trellis did not appear to have a clear trend, although it did effect COH levels.

Table 3.30. Concentration of cohumulone (COH) in hop cones across treatments and years.

		Cohumulone (COH) Concentration (%)	
Trellis	**Cultivar**	**2024**	**2025**
Straight	**'Cascade'**	2.8 ± 0.3 abB	2.2 ± 0.3 abB
	'Chinook'	3.1 ± 0.2 aA	2.5 ± 0.2 aB
	'Magnum'	1.5 ± 0.3 bB	1.2 ± 0.3 bB
V	**'Cascade'**	1.8 ± 0.2 bB	2.3 ± 0.2 aB
	'Chinook'	2.7 ± 0.3 abB	2.2 ± 0.3 abB
	'Magnum'	1.9 ± 0.2 bA	0.8 ± 0.3 bB

[i] Values are represented as mean ± standard error.

[ii] Values followed by similar lowercase letters among trellis and cultivar within year indicate no significant difference (α > 0.05) according to Tukey's HSD.

[iii] Values followed by similar uppercase letters among years within cultivar and trellis indicate no significant difference (α > 0.05) according to Tukey's HSD.

In 2024, 'Chinook' and 'Magnum' had the highest levels of adhumulone (ADH) (9.1 ± 0.4 and 10.1 ± 0.4 %, respectively). In 2025, 'Chinook' again had the highest ADH (7.3 ± 0.4 %), with 'Cascade having intermediate concentration (5.9 ± 0.4 %) and 'Magnum' being the least concentrated (5.6 ± 0.5 %). When comparing overall ADH between the two years, concentration in 'Cascade' did not have a major change, but ADH in 'Chinook' and 'Magnum' decreased significantly from 2024 to 2025 (Table 3.31).

Regarding trellis effects on ADH concentration, the straight trellis slightly favored, especially for 'Cascade' in 2024 and 'Magnum' in 2025. Similar to COH, overall ADH concentrations decreased from 2024 to 2025 for 'Chinook' and 'Magnum', while 'Cascade' remained stable (Table 3.32).

Table 3.31. Concentration of adhumulone (ADH) in hop cone width across cultivars and years.

	Adhumulone (ADH) Concentration (%)	
Cultivar	**2024**	**2025**
'Cascade'	6.6 ± 0.4 bB	5.9 ± 0.4 abB
'Chinook'	9.1 ± 0.4 aA	7.3 ± 0.4 aB
'Magnum'	10.1 ± 0.4 aA	5.6 ± 0.5 bB

[i] Values are represented as mean ± standard error.

[ii] Values followed by similar lowercase letters among cultivars within year indicate no significant difference (α > 0.05) according to Tukey's HSD.

[iii] Values followed by similar uppercase letters among years within cultivar indicate no significant difference (α > 0.05) according to Tukey's HSD.

Table 3.32. Concentration of adhumulone (ADH) of hop cones across treatments and years.

		Adhumulone (ADH) Concentration (%)	
Trellis	**Cultivar**	**2024**	**2025**
Straight	**‘Cascade’**	7.8 ± 0.6 abA	5.9 ± 0.6 abB
	‘Chinook’	9.4 ± 0.6 aA	7.6 ± 0.6 aB
	‘Magnum’	10.0 ± 0.6 aA	7.4 ± 0.6 aB
V	**‘Cascade’**	5.5 ± 0.6 bB	5.6 ± 0.6 abB
	‘Chinook’	8.8 ± 0.6 aA	7.1 ± 0.6 aB
	‘Magnum’	10.2 ± 0.6 aA	3.7 ± 0.7 bB

[i] Values are represented as mean ± standard error.

[ii] Values followed by similar lowercase letters among trellis and cultivar within year indicate no significant difference (α > 0.05) according to Tukey’s HSD.

[iii] Values followed by similar uppercase letters among years within cultivar and trellis indicate no significant difference (α > 0.05) according to Tukey’s HSD.

In 2024, colupulone (COL) was highest for ‘Cascade’ on the straight trellis (2.1 ± 0.2 %) and all other combinations were statistically similar. In 2025, ‘Cascade’ again had the highest concentrations, but for both trellises. ‘Chinook’ had intermediate concentrations, especially on the straight trellis. Overall COL concentrations remained stable from 2024 to 2025 when on the straight trellis, but ‘Magnum’ on the V-trellis decreased and ‘Cascade’ on the V-trellis increased (Table 3.33).

When comparing trellis type alone, the overall COL concentrations in 2024 were significantly higher on the straight trellis (1.4 ± 0.1 %) than the V-trellis (1.1 ± 0.1 %). In 2025, there was no significant effect. COL concentrations on the straight trellis were significantly higher in 2024 than 2025 (decreased to 1.2 ± 0.1 %) (Table 3.34).

Table 3.33. Concentration of colupulone (COL) of hop cones across treatments and years.

		Colupulone (COL) Concentration (%)	
Trellis	**Cultivar**	**2024**	**2025**
Straight	**‘Cascade’**	2.1 ± 0.2 aB	1.8 ± 0.2 aB
	‘Chinook’	1.2 ± 0.1 bB	1.1 ± 0.1 abB
	‘Magnum’	1.0 ± 0.2 bB	0.7 ± 0.2 bB
V	**‘Cascade’**	1.4 ± 0.1 bB	1.8 ± 0.1 aA
	‘Chinook’	1.0 ± 0.2 bB	1.0 ± 0.2 bB
	‘Magnum’	0.9 ± 0.1 bA	0.4 ± 0.2 bB

[i] Values are represented as mean ± standard error.

[ii] Values followed by similar lowercase letters among trellis and cultivar within year indicate no significant difference (α > 0.05) according to Tukey's HSD.
[iii] Values followed by similar uppercase letters among years within cultivar and trellis indicate no significant difference (α > 0.05) according to Tukey's HSD.

Table 3.34. Concentration of colupulone (COL) in hop cone width across cultivars and years.

	Colupulone (COL) Concentration (%)	
Trellis	**2024**	**2025**
Straight	1.4 ± 0.1 aA	1.2 ± 0.1 bB
V	1.1 ± 0.1 bB	1.1 ± 0.1 bB

[i] Values are represented as mean ± standard error.
[ii] Values followed by similar lowercase letters among trellises within year indicate no significant difference (α > 0.05) according to Tukey's HSD.
[iii] Values followed by similar uppercase letters among years within trellis indicate no significant difference (α > 0.05) according to Tukey's HSD.

Finally, for adhumulone (ADL) in both years, 'Cascade' and 'Magnum' had the highest concentrations, regardless of treatment (1.8 – 2.3 % in 2024 and 1.6 – 1.8 % in 2025). However, in 2025, 'Magnum' was only highest on the straight trellis. From 2024 to 2025, 'Cascade' on the straight trellis and 'Magnum' on the V-trellis had a decrease in ADL, while other treatment combinations remained stable (Table 3.35).

Table 3.35. Concentration of adhumulone (ADL) of hop cones across treatments and years.

		Adhumulone (ADL) Concentration (%)	
Trellis	**Cultivar**	**2024**	**2025**
Straight	**'Cascade'**	2.3 ± 0.2 aA	1.7 ± 0.2 aB
	'Chinook'	1.1 ± 0.2 bB	0.9 ± 0.2 bB
	'Magnum'	2.1 ± 0.2 aB	1.8 ± 0.2 aB
V	**'Cascade'**	1.8 ± 0.2 aB	1.6 ± 0.2 aB
	'Chinook'	0.9 ± 0.2 bB	0.9 ± 0.2 bB
	'Magnum'	2.1 ± 0.2 aA	0.9 ± 0.2 bB

[i] Values are represented as mean ± standard error.
[ii] Values followed by similar lowercase letters among trellis and cultivar within year indicate no significant difference (α > 0.05) according to Tukey's HSD.
[iii] Values followed by similar uppercase letters among years within cultivar and trellis indicate no significant difference (α > 0.05) according to Tukey's HSD.

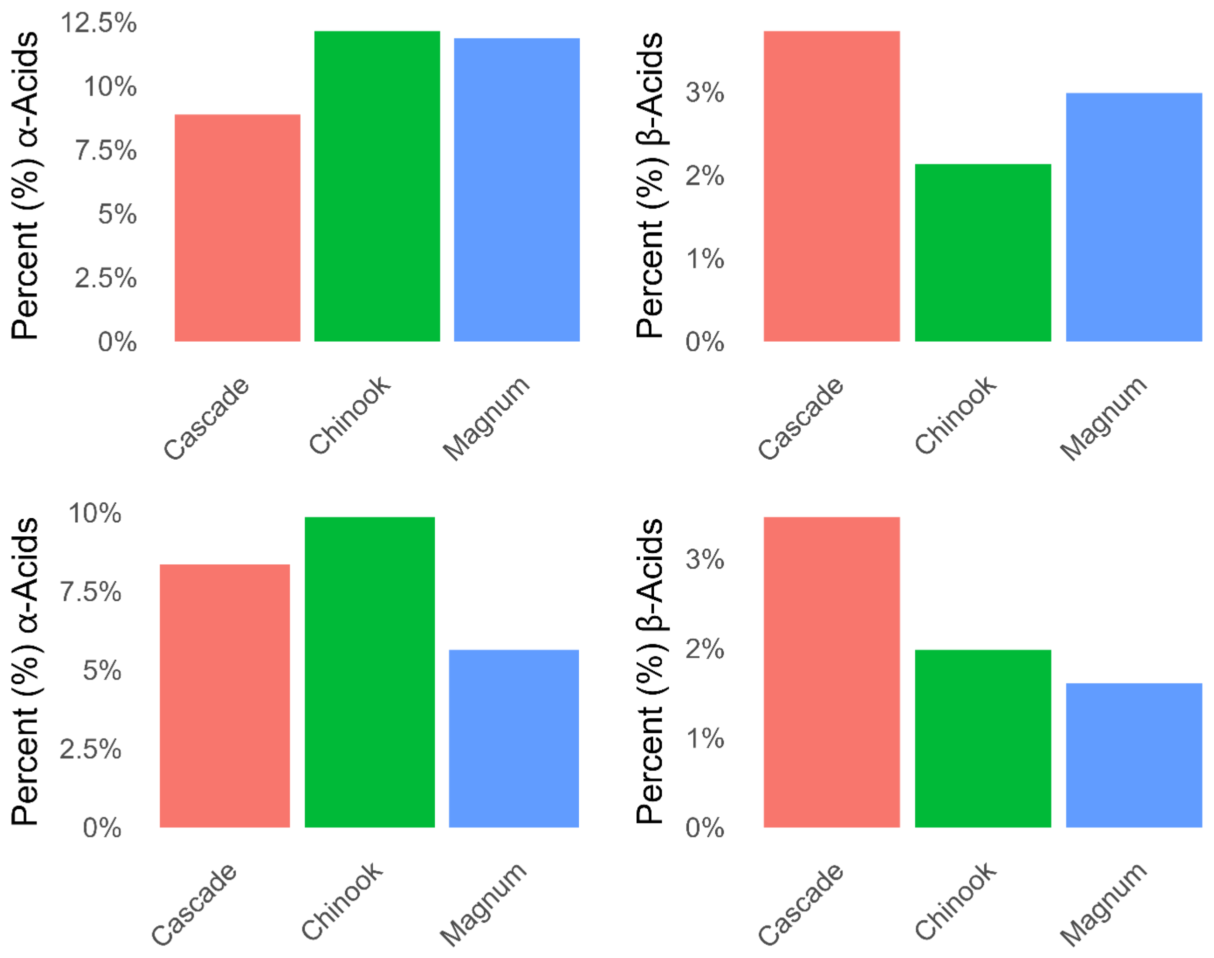

Figure 3.15. Average total percentage of α− and β-acids for each cultivar in 2024 (top row) and 2025 (bottom row).

3.4. Discussion

During this portion of the study, the removal of Neo1 during the cone stage of 2024 limits some conclusions on *Humulus neomexicanus* in Alabama (i.e., yield and subsequent year performance). Additionally, overcast conditions during LAI measurements, and some biological measurements, may underestimate canopy density and performance. Pest pressure from spider mites was noted but not quantified, leaving uncertainty about its impact.

Weather patterns between 2024 and 2025 were similar, except for a significantly higher UV index in 2025. UV index, solar radiation, and air temperatures peaked from June to August during the developmental stage of cones, possibly causing more stress on the plants and limiting yield potential (Agehara and Marceddu, 2025). UV index specifically may have contributed to the photoinhibition and stress responses measured in the photosynthetic variables, especially during cone development within this year (Eriksen et al., 2020; Kosobryukhov et al., 2020). Previous studies (Mozny et al., 2023) suggest that high UV and heat can reduce hop quality and yield, aligning with the decline in a and b-acid concentration in 2025.

Certain patterns that were found within the field data for the hops within this experiment. Regarding height, all cultivars reached trellis height by the cone stage, capping vertical growth and minimizing late-season differences. It is possible that the limitations of the structure masked further potential advantages for the cultivars beyond 457 cm (15 ft, 4.6 m). As discussed in previous studies (Darby, 2004; Agehara et al., 2020), taller trellises (18-20 ft, 5.5-6 m) may have allowed for continued elongation and higher yields, whereas the 15-ft (4.6 m) trellis used here likely restricted further growth potential. Gallardo et al. (2025) found that in Florida, increasing the trellis height (from 12 ft/3.7 m, to 15 ft/4.6 m, to 18 ft/5.5 m) resulted in more uniformity of vertical cone distribution. In addition, when considering the effect of trellis, while supplemental lighting enabled adequate vertical growth on both trellis systems, environmental stress during reproductive stages likely overshadowed any structural benefits (Leles et al., 2023).

LAI ranged, on average, from about 0.2 to 1.0 m^2/m^2, but was as high as 5 m^2/m^2 or more in some instances (especially for ‘Cascade’). In the second year, LAI values were significantly lower, likely due to late-season and environmental stress, and it can be assumed that LAI did not reach its full potential before harvest. While there has been little to no research on measuring LAI of hops using the ACCUPAR LP-80, typical values for similar crops, such as grapes, ranged from 1.5 to 3.5 m^2/m^2 in one study (Kargar et al., 2019). For row crops, like soybeans and corn, LAI can range from 1.5 to 6.5 m^2/m^2 (Adeboye et al., 2019; Pokovai and Fodor, 2019). Thus, the estimate range for hop plants is about 1.5 to 5 m^2/m^2. While some outliers achieved this canopy density, due to the lack of previous methodology for hops using this device, and the tall, vertical growth habit of the crop, it is unknown if results reflect canopy density with the greatest accuracy.

Studies in northern regions showed that V-trellises improve biomass and yield, possibly having increased success due to the longer growing seasons and cooler conditions in those climates (Agehara et al., 2020; Ježek & Matthews, 2019). However, a recent study in Florida found that the V-trellis (especially combined with a taller trellis system) can improve biomass and yield by 24% (and by 215% when increasing trellis height alone), even in the first year (Gallardo et al., 2025). The straight trellis system in the study by Gallardo et al. (2025) used two twines per hill and the V-trellis used four twines per hill, as opposed to our one twine for the straight trellis and two twines for the V-trellis. Gallardo et al. (2025) also trained 16 bines for both trellis systems, while we trained two for the straight and 4 for the V-trellis. The results from Gallardo et al. (2025) contrast to our study, in which the V-trellis did not have a significant yield or biomass advantage. This is possibly due to unique environmental stressors, fewer bines trained, and/or maturity of the hop plants affecting the results of our particular methodology.

Because hops need "several years to establish before reaching full yield potential", it is likely that once hops mature, the V-trellis may become more beneficial (Agehara et al., 2016). Additionally, more improved management (such as ideal harvest times, refined irrigation and IPM, more routine soil testing, etc.) within this experiment could also lead to better yield potential for this treatment. Furthermore, V-trellis demands more biomass output per one plant than straight trellis; therefore, one method to see improvement on the V-trellis may be to use two or more transplants (rhizomes or containerized transplants) per hill instead of one.

Regarding soil quality in this experiment, pH decreased significantly to 4.5 in 2025. This was likely due to the use of an ammonia-based nitrogen fertilizer (Daniel, 2019). In the future, using nitrate-based fertilizers, such as calcium nitrate, to supply nitrogen would be recommended. Additionally, Alabama farmers should test the soils in their hop yard multiple times. This includes before planting, throughout the growing season, and after the growing season is over, before plants emerge for the next season (Clark, 2023). Plants that are being grown in acidic soil, especially hops, cannot properly uptake the nutrients that they need, even if you are supplying enough (USDA, 2022).

Photosynthetic parameters (*A*, gs, and ETR) were lower in the cone stage and not different among cultivars in each growth stage for both years. These variables followed a clear pattern: high performance during vegetative growth (when canopy expansion was prioritized) and a sharp decline during the cone stage. This corresponds with a previous study (Eriksen et al., 2020) in which photosynthetic efficiency is reduced by heat stress. These physiological responses explain the disconnect between early growth and final yield.

In contrast, Chl was highest during the flower and cone stages, suggesting better nitrogen retention during these times. A high Chl during reproductive stages and stress are common and may imply that plants are increasing chlorophyll to support energy-demanding circumstances (like producing cones and/or mitigating stress) (Bheemanahalli et al., 2022).

Overall, trellis had no significant or notable effect on plant height, *A*, ETR, or LAI, and while it was significant in some instances for gs and Chl, there was no consistent pattern for the effect of trellis on these variables. This suggests that structural differences between the trellis types did not strongly influence physiological performance under Alabama conditions. In addition, photosynthetic responses decreased in the reproductive stages, likely due to the shift in energy when producing cones, leaf senescence, and/or stress from increased heat and UV in the summer months.

Discussing specific cultivar performance, ‘Cascade’ was the fastest to reach maximum height in the first year during bine development and had the tallest weekly plant height in both years. This indicates high vigor and trellis utilization, as well as cultivar adaptability. The quick development may have also determined the biomass and yield potential, as leaf area index (overall canopy density) and cone yield were among the highest. Stomatal conductance for ‘Cascade’ remained stable across all growth stages in 2024, while it dropped off during the cone stage for other cultivars. This indicates that ‘Cascade’ was better at resource management and may have had a later senescence of the leaves (Gloser et al, 2024). ‘Cascade’ also continued a high pattern of electron transport rate, similar to ‘Neo1’, during the vegetative and flower stages in 2024, suggesting strong photosynthetic activity in the earlier stages (Eriksen et al., 2020). In both years, ‘Cascade’ had the highest chlorophyll index during the cone stage, meaning that it allocated more energy to cone production compared to other cultivars (Liu et al., 2019).

In 2025, ‘Chinook’ reached maximum trellis height before any other cultivars and with ‘Cascade’, had the tallest plant heights each week compared to other cultivars. While plants collectively in the vegetative stage of 2025 grew taller compared to the previous year, ‘Chinook’ in particular had an increase in vigor and cultivar adaptability over time. This shift suggests that ‘Chinook’ may have acclimated better to the second-year conditions or benefited from a dormancy period in which root systems built up carbohydrate reserves and improved bud development (Wimmer, 2024). Furthermore, following behind ‘Cascade’, ‘Chinook’ had among the highest leaf area index results, representing a great amount of biomass accumulation for the cultivar. Electron transport rate for ‘Chinook’ decreased during both reproductive stages (flowering and cone), suggesting less photosynthetic capacity compared to ‘Cascade’ during early reproduction (Eriksen et al., 2020).

‘Magnum’ had the lowest plant heights in both years, highlighting poor vigor and adaptability. Additionally, photosynthesis rate for this cultivar in 2024 dropped from 20.6 ± 1.5 μmol CO_2 m^{-2} s^{-1} in the vegetative stage to 14.4 ± 1.5 μmol CO_2 m^{-2} s^{-1} in the flower stage while other cultivars remained stable, indicating a decrease in productivity during early reproductive stages. Similar to ‘Chinook’, electron transport rate for ‘Magnum’ decreased during the flowering and cone stages. In both years, ‘Magnum’ had among the lowest chlorophyll index overall, demonstrating a high energy demand under stress (Bheemanahalli et al., 2022). In summary, ‘Magnum’ in the field does not perform as well as ‘Cascade’ and ‘Chinook’ in Alabama.

‘Neo1’ during the early stages of this experiment showed promise. Along with ‘Cascade’, this cultivar had the tallest weekly plant height in 2024, indicating sufficient establishment and vigor. While ‘Neo1’ had similar leaf area index results as ‘Chinook’, there was a severe loss of foliage in the later season. When analyzing its biological efficiencies, electron transport rate remained high for ‘Neo1’ during the flowering stage, indicating a continual and strong level photosynthetic activity. However, stomatal conductance for ‘Neo1’ was lower across all growth stages compared to other cultivars. This suggests that these plants had a lower CO_2 uptake, limiting photosynthesis (Kenny, 2005). A consistently low gs is likely to result in lower biomass accumulation, smaller or undeveloped cones, and overall poor performance under stress (Kenny, 2005). In the end, no cones from 'Neo1' were harvested, and it can be assumed that this cultivar over did not perform well in Alabama. This contrasts a previous study by Pearson et al. (2016) in which 'Neo1' outperformed cultivars like 'Chinook', especially in the second year of growth. However, this aforementioned Florida study was performed under an open greenhouse structure, lending to the idea that 'Neo1' may perform better when protected from rainfall and other environmental elements.

During the harvest and post-harvest analysis of cones, it was found that, similar to many field parameters, trellis had no effect on cone length or cone yield (as previously mentioned). Additionally, while some trellis effects were present, there was no consistent pattern of this on cone width or composition (α- and β-acids).

The lack of trellis effect on yield contrasts with studies in northern regions (i.e., Darby, 2004), where V-trellises improved productivity. This discrepancy may stem from the soil pH decline, Alabama's heat stress, or earliness in the plants' establishment. In general, cultivar and year-to year differences were the dominant factors influencing yield performance. Overall, yields in this experiment decreased substantially from 2024 (2,160.1 ± 368.6 kg ha^{-1} FCY) to 2025 (720 ± 150.6 kg ha^{-1} FCY), aligning with the findings of decreased productivity and increased biological stress in the reproductive stages.

As mentioned, 'Cascade' had among the highest yields in 2024 (2,787 ± 755.2 kg ha^{-1} FCY) and 2025 (although decreased to 573.7 ± 155.5 kg ha^{-1} FCY). This is consistent with its adaptability reported in previous Southeastern trials (i.e., Acosta-Rangel et al., 2021). Yields for 'Cascade' can range from about 2,000 to 2,500 kg ha^{-1} DCY (USDA, 2025), which our study fell below (only about 800 kg ha^{-1} of DCY in the first year). A study in Florida found that yield increased from about 250 kg ha^{-1} in year one to 465 kg ha^{-1} DCY in year two under similar conditions (use of supplemental lighting and straight and V-trellising) (Gallardo et al., 2025). The increase from year one to year two may suggest a higher yield potential, perhaps doubling, for 'Cascade' in year two had the conditions been ideal.

'Chinook' also had one of the highest cone yields (an average 2,324.1 ± 629.8 kg ha^{-1} in 2024 and 573.7 ± 155.5 kg ha^{-1} in 2025 of FCY), like that of 'Cascade'. Yield potential for 'Chinook' in ideal conditions is also similar to 'Cascade' with a range of 2,000 to 2,700 kg ha^{-1} DCY (USDA, 2025). In our study, only about 600 kg ha^{-1} of DCY was achieved (2024). Acosta-Rangel et al. (2021) found 'Chinook' to have yields of under 200 kg ha^{-1} (DCY), and this cultivar was not among the highest ranking ('Chinook', 'CTZ', and 'Nugget' had the best yields). This contrasts to our study in which 'Chinook' had some of the best yields and performance.

'Magnum' had the lowest cone yield of only 671.4 ± 181.9 kg ha^{-1} FCY on average (2024). This, like the results from the field variables, indicates that 'Magnum' may be poorly adapted to Alabama's heat, UV stress, and other conditions, despite its disease resistance. The USDA (2025) describes 'Magnum' (or 'Hallertauer Magnum', it is also called) as having yields of less than 2,000 kg ha^{-1} DCY on average. In the study by Acosta-Rangel et al. (2021), 'Magnum' was among the lowest performing (like 'Chinook' in their study), with yields falling below 200 kg ha^{-1} (DCY). In our study, 'Magnum' also had yields falling bellow 200 kg ha^{-1} (DCY), demonstrating a repeated lack of adaptability for this cultivar.

Cone size, in some instances, increased, possibly due to the establishment of the plant of time (Guimarães, 2020). It can be expected that cone size will increase by year three. The variability in cone size can also be due to the subtropical climate, in which rain can positively influence cone development, but heat stress can reduce size and quality (Donner at al., 2020).

Numeric values of cone size have not been universally determined, and within the industry, cones are typically described as small, medium, or large. However, cone length can range from a little over one cm (0.5 inch), on the smaller side, to a maximum of 10 cm (4 inches), in which cones are extremely large (Borgman, 2016). Additionally, a previous study classified small cones as being less than 2 cm, medium cones as 2 – 3.2 cm, and large cones as 3.4 cm or more (Raut et al., 2020). Leles et al. (2023) found cone lengths to be between 1.8 and 2.5 cm, and cone widths between 0.9 and 1.9 cm for cultivars such as 'Hallertau Mitelfruher', 'Mapuche', 'Northern Brewer', 'Spalter', and 'Yakima Gold' in the first year of production. While these cones were smaller than anticipated for their respective cultivars, in the initial years of hop cultivation, "…cones are not uniform in terms of size and mass", so it is common for the cones to be smaller during this time (Leles et al, 2023) (Guimarães, 2020). This is similar to the results of our study, in which cones in general were smaller than the typical description.

For example, according to general industry expectations, 'Cascade' cones are medium, dense cones (Yakima Valley Hops, 2025; Great Leak Hops, 2019). One study determined that 'Cascade' averaged 2.7 cm in length and 1.7 cm in width in their first year being grown under a similar climate (humid subtropical) (Giacomini et al. 2023). This was similar to our study in that 'Cascade' had an average length of about 2.1 cm and a width of 1.6 – 1.7 cm. While 'Cascade' did not have cones quite as long as 'Chinook', their length exceeded that of 'Magnum'.

'Chinook' cones, like 'Cascade', are expected to be medium to large and dense (Yakima Valley Hops, 2025; Great Leak Hops, 2019). In the study by Giacomini et al. (2023), 'Chinook' averaged a length of 3.6 cm and a width of 2.1 cm. In our study, however, ‘Chinook’ had a length of about 2.5 cm and a width of about 1.9 – 2.4 cm, shorter than that of the results from Giacomini et al. (2023). Overall, ‘Chinook’ had the largest cones in both years during this experiment. Additionally, cone width increased in the second year for this cultivar, likely due to the establishment of the plant. However, the ability of ‘Chinook’ to maintain larger cone size under stress may also suggest a cultivar-specific resilience trait, aligning with Rodolfi et al. (2019), who noted that larger cones can occur under adverse conditions.

‘Magnum’ cones are commonly described as large and heavy in the industry (Yakima Valley Hops, 2025; Great Leak Hops, 2019). However, in this study, ‘Magnum’ had the shortest cones overall (an average of 1.9 ± 0.1 cm). Like ‘Chinook’, width of these hop cones increased in the second year, likely due to plant establishment and/or a response to adverse conditions.

α- and β-acids in general also decreased significantly in the second year. This could be due to heat and UV stress impairing secondary metabolite synthesis (Hagemann et al., 2024). The decrease in β-acids was less pronounced; however, these compounds were already significantly lower in the hop cones than expected on the industry scale. β-acids are highly prone to oxidation by air and heat, and in subtropical conditions, high temperatures, oxygen exposure and humidity can form degradation products like tricyclopulone (Krofta et al., 2013). Additionally, β-acids do not have the tertiary alcohol group that is present in α-acids, which means they cannot isomerize and are more vulnerable to oxidation (Krofta et al., 2013).

Sensory panel results typically revealed cultivar-specific aroma profiles consistent with industry expectations, but variability in responses indicates the need for controlled brewing trials to validate market potential.

The α-acids for 'Cascade' were about 9.4% in 2024 and 8.1% in 2025. β-acids were 4.4% in 2024 and 3.5% in 2025. 'Cascade' was the least susceptible to a decrease in α-acids compared to other cultivars. Panelists from this study determined that 'Cascade' had a flavor and aroma profile of earthy and woody, with a strong presence of vanilla aroma. For industry expectations, α-acids range from 4.5 – 7.0% and β-acids range from 4.8 – 7.0%. Additionally, expected flavors and aromas (in the scope of what we tested for) are citrus, woody, and other (floral, grapefruit, pine) (Haas, 2022). In summary, 'Cascade' met or exceeded many industry standards, especially for α-acids. However, the range of β-acids was lower than desired, and the floral element was missing (although, it was not directly assigned during the tea panel).

'Chinook' had an average of 12.2% α-acids in 2024, and 9.8% in 2025. For β-acids, 2.3% in 2024 and 2.0% in 2025 were obtained. 'Chinook' was least susceptible to β-acid degradation compared to other cultivars. Based on the tea panel, 'Chinook' had a spicy, woody flavor and a citrusy, spicy, earthy, and woody aroma, making it the most robust cultivar in terms of flavor and aroma within this study. Within the industry, 12 – 14% α-acids and 3 – 4% of β-acids are expected. 'Chinook' is predicted to have a citrus, spicy, woody, and other (sweet fruit, grapefruit, apricot, pine resin, juniper) flavor and aroma (Haas, 2022). Like 'Cascade;, 'Chinook' hit the mark for α-acids, but β-acid content was slightly lower than expected. This cultivar also achieved the complex flavor and aroma profile, apart from unreported notes.

Finally, 'Magnum' had a concentration of 11.6% α-acids in 2024 and 6.8% in 2025. For β-acids, this cultivar has 3.1% in 2024 and 2.5% in 2025. 'Magnum' was very susceptible to having a decrease α-acids, especially. According to panelists, 'Magnum' had the least complex flavor and aroma, only being described as earthy and woody. This cultivar is expected to have an α-acid concentration of 11 – 16% and 5 – 7 % β-acids. The flavor and aroma has also been described as citrus and other (grassy, methol, green fruit, lemon, green pepper, spearmint, apple). ‘Magnum’ was the furthest from meeting industry expectations. Both α- and β-acid content was far below the anticipated threshold and was more often described as having an earthy or woody profile as opposed to citrus.

3.5 Conclusion

This study demonstrated that hop cultivar performance in Alabama is strongly influenced by physiological responses, stages of development, cultivar-specific traits, and possibly environmental influences rather than trellis design alone. ‘Cascade’ and ‘Chinook’ produced the highest yields. ‘Magnum’ consistently exhibited low yield potential and growth, suggesting limited adaptability to the region’s climate. Yields overall declined significantly in the second year, likely due to environmental stressors. ‘Neo1’ failed to produce cones due to severe stress, despite its early promise for performance.

Leaf area index and photosynthetic efficiencies confirmed that early vegetative vigor does not guarantee reproductive success; physiological indicators such as stomatal conductance and water use efficiency declined sharply during cone development, especially in 2025. These findings highlight the critical role of potential environmental stress (heat, UV radiation, soil pH, etc.) in limiting cone formation and secondary metabolite synthesis. a and b-acid concentrations decreased substantially in the second year, reducing cone quality and reinforcing the sensitivity of hop chemistry to climatic extremes.

Largely, cultivar selection emerged as the most influential factor for successful hop production in Alabama. ‘Cascade’ and ‘Chinook’ demonstrated the greatest adaptability, though their performance varied by year, emphasizing the need for multi-year trials. Trellis system effects were minimal, suggesting that structural modifications alone may not be able to achieve increased yields in the event of stress and/or plant establishment in the first few years. Future research should focus on integrated stress management strategies, soil pH stabilization, pest control, and ideal harvest dates, as well as exploring irrigation and fertilization regimes to mitigate reproductive stress. Additionally, studying the effects of partial shading on hops, especially during peak heat and UV stress, can assist in mitigating yield loss from these climatic challenges. These results provide foundational insights for establishing sustainable hop production in the nontraditional environments of the Southeastern United States.

Chapter 4: Final Conclusions

These experiments evaluated several critical aspects of hop production in Alabama, including mulching strategies for increased performance and yield, cultivar performance under different trellis systems, and the resulting post-harvest cone quality. These trials provide insights into adapting hops to a subtropical environment, which is atypical for the crop. During the first experiment, mulching was found to significantly influence early growth and yield under conditions of decreased rainfall and increased heat and solar radiation. Black fabric mulch supported greater bine growth and yield, likely by improving soil moisture retention and temperature regulation. The findings from this experiment support previous studies in which mulching is demonstrated to mitigate heat and drought stress for perennial crops.

In the second experiment, cultivar selection had the largest effect on biological responses, biomass accumulation, cone quality, and yield. More specifically, ‘Cascade’ and ‘Chinook’ had the highest biomass and yield. ‘Magnum’ had the lowest performance and yield potential of all harvestable cultivars in both years. ‘Neo1’, while having positive initial performance, declined rapidly during the cone stage and did not produce any yield under high stress. ‘Nugget’ was not evaluated during this experiment due to its lack of emergence and viability. Additionally, while trellis system was expected to influence performance and yield, it had minimal significance for most variables, and the V-trellis system did not improve yield at this time as expected.

Regarding biological performance, while the hop plants in 2025 started out with positive responses, heat stress, high UV, and acidic soils likely caused a major decline in photosynthetic efficiencies by the early cone stages, decreasing overall yield. Additionally, a- and b-acid content is subject to decrease, indicating the sensitivity of these compounds in under stress. The cultivar

‘Cascade’ was less susceptible to α-acid degradation, and ‘Chinook’ was less susceptible to β-acid degradation. Both cultivars met most industry expectations (especially in 2024) and provide a great option for farmers to growth a bittering-hop with a desirable flavor and aroma profile.

Overall, these results demonstrate that successful hop production in Alabama requires careful cultivar selection, proper pH and fertilizer management, mulching for soil moisture and temperature control (especially black fabric), integrated pest management, supplemental lighting to extend day length, and irrigation to mitigate drought stress. Future work should focus on trials spanning several years, as opposed to just one or two, to further understand year-to-year differences. Testing these cultivars further, along with other cultivars, would also be beneficial, as more heat-tolerant, adaptable options may be discoverable.

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