Beer: The Key to Hoppiness

A Memoir

A Major Qualifying Project Report
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Abstract

The microbrewery industry is on the rise - these small-scale operations brew beer in small batch processes, leaving little room for experimentation on new beers. Our project aids Purgatory Beer Company in developing a new beer product by testing different combinations and concentrations of hops and chemically analyzing their flavors, aroma, and chemical structures. Our experiments determined that the amount of different hops used in a beer influences the flavor associated of a single hop. Additionally, our team analyzed trends in chemical compounds associated with the appealing and unappealing taste of the hopped beer samples. We suggest further research should be done using a more standardized panel tasting procedure with larger numbers on the panel.

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1. Introduction

The beer industry in the United States has seen a shift towards traditional craft brewing within the past two decades. The majority of local craft breweries are classified as microbreweries - that is, the brewery produces less than 15,000 barrels of beer per year and sell the majority of its beer on site. Since the 1980s, the number of microbreweries in the United States has grown exponentially, and these trends show no sign of stopping (Brewers Association, Weston, Herrmann, & Davidoff, 1999).

Purgatory Beer Company is a small microbrewery, located in Whitinsville, MA. Purgatory was started by two co-owners, Kevin Mulvehill and Brian DiStefano, who wanted to share their passion and love for locally brewed beer. While the co-owners of Purgatory both have a deep understanding of the brewing process, they wanted to gain a more in-depth knowledge of the technical and scientific side of beer production. The co-owners of Purgatory specifically wanted to learn more about how different hops interact, more specifically what is happening at the chemical level when different types of hops were combined at different concentrations, and what chemical components contribute to the best-tasting beers.

The goal for our Major Qualifying Project is to provide Purgatory Beer Company with chemical data about different hops combinations and concentrations, so the co-owners of Purgatory can create the best beers possible. To achieve this goal, we dry-hopped different hop quantities and combinations, using both a Bud Light and Purgatory's beer as a base. We performed taste tests to qualitatively determine our sponsor's favorite combinations. We then analyzed the different hop combinations using GC-MS, IR Spectroscopy, pH tests, and specific gravity tests. Finally, we used these results to analyze the chemical compounds, pH, and specific gravity of the beers that scored well within the taste tests (or the favorable, good beers) and the beers that did not score well within the taste tests. From this data, we tried to fit correlations so we could predict the resulting flavors of new combinations.

2. Background

Throughout history, beer in one shape or another, has existed as a form of light alcoholic beverage. It is important to first understand the industry and the process used in creating this iconic beverage. This section goes into the details on information needed to understand the science behind the beverage loved around the world.

2.1 Micro-brewing and Purgatory

Beer is the one of the most popular alcoholic beverages in the world, and is the most consumed beverage behind water and tea worldwide (Nelson, 2004). Beer originally came to America's shores with the Pilgrims, and since then beer production has grown into the multi-billion-dollar industry that it is today. Presently, Anheuser-Busch, Miller-Coors, and Constellation control over 75% of the United State's brewing industry, with lagers dominating the majority of US beer production (NBWA Industry Fast Facts, 2017).

In light of the success of these large beer corporations, many brewers worried the traditional aspects of beer brewing would be lost forever. The past few decades have seen the rise of craft breweries, all working to preserve these brewing traditions, brewing more "innovative" beers, and bring localism and community back to brewing (Mittelman, 2008). The craft brewing industry has seen a lot of growth in the past few decades - in 1983 there were only 43 craft breweries in the US (Weston, Herrmann, & Davidoff, 1999), and in 2017 there were over 6,000 (Brewers Association). Over half of these craft breweries can be classified as microbreweries, which are defined as breweries that produce less than 15,000 barrels of beer per year (Brewers Association, n.d.). Our sponsor, Purgatory Beer Company, is a microbrewery that opened in 2016 and is located in Whitinsville, MA. Similar to the rest of the craft brewing sector, Purgatory has seen much growth within their business in the past few years. As their business grows, the owners of Purgatory, Brian Distefano and Kevin Mulvehill, are increasingly interested in learning about the technical side of brewing. Through our work, we hope to help Purgatory Beer Co. gain more information regarding the technical side of independent craft brewing.

2.2 How is beer brewed

The process of brewing beer remains relatively constant despite the many different variations and types. The four main ingredients used in all brewing processes are malts (usually barley, but sometimes also wheat, or rye), water, yeast, and hops (Briggs, Boulton, Brookes & Stevens, 2004). There are four main parts of every brewing process. These include: malting, boiling, cooling, and fermenting. A flow map of the entire process can be seen in Figure 1 and is described in more detail below.

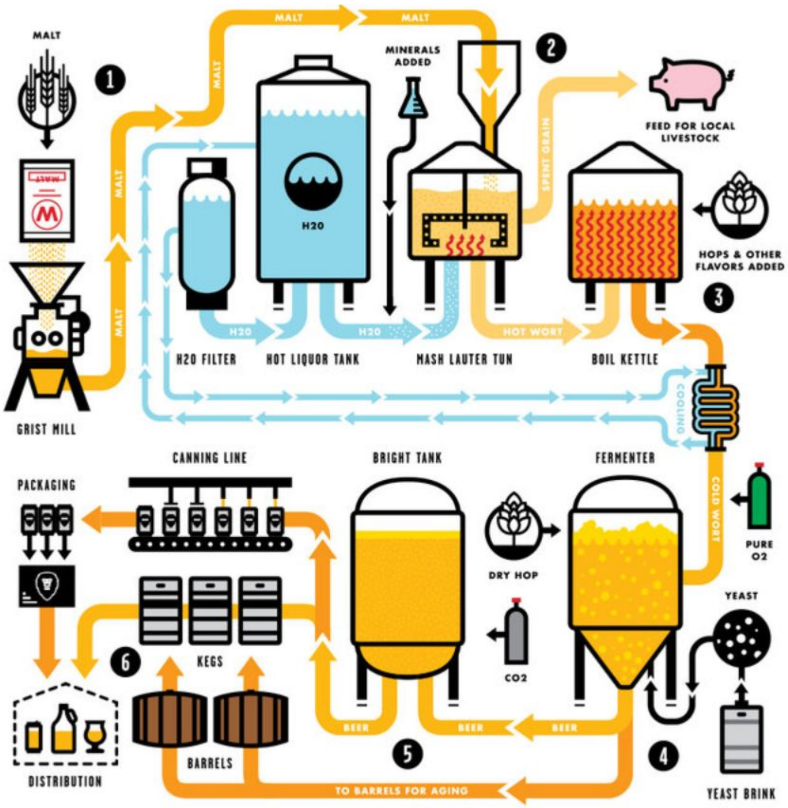

Figure 1: *Flow diagram of the brewing process (Trosset, 2018).*

Brewing first starts with the mashing of milled malts with warm water. Grains are malted when they have endured a controlled germination stage which breaks endosperms and creates enzymes. Once the grains are germinated, the grain is steeped, by immersion in water at a specific temperature, typically from 144-158 degrees Fahrenheit to activate the enzymes in the malt (Trosset, 2018). The active enzymes convert the available starches in the malt into maltose and dextrins. This sugary liquid is called "wort." Distinct malts create different enzymes and therefore require different conditions such as temperature, mixing time, and drying process, to ensure the enzyme activates and is not damaged. Once the enzymes are activated and the maltose and dextrins are produced, the liquid produced is separated from the grain and sent to the boil kettle (Briggs et al., 2004). The grain, a byproduct, is typically given to local farmers to use as food for their livestock.

The second phase of the brewing process is the boiling of the wort. Boiling the wort has two main purposes: to pasteurize the wort. Also in this phase, hops are added to the boiling wort bring about bitterness and aroma changes. Boiling of the wort typically occurs for one to two hours, during which some of the solution evaporates. A reduction in wort volume between 7 to 10% is typical (Briggs et al., 2004). Hops are added at different times throughout the boil for various reasons. Hops added at the beginning of the boil mainly affect the bitterness of the final product - the longer hops are boiled in the wort, the more bitter the final beer taste will be. Alternatively, hops that are added at the end of the boil will be less influential in beer bitterness and impart more of their distinct flavor (Trosset, 2018). There are many different type of hops which will be further discussed in Section 2.3. After the beer is boiled for the appropriate amount of time, it is cooled and moved into a fermenter.

Fermentation is the final step in the brewing process before the beer can be consumed, packaged, or distributed. Yeast is a living organism and can only survive in specific conditions and environments; consequently the boiled wort must be cooled to a temperature usually around 60 to 70 degrees Fahrenheit (Trosset, 2018). The temperature that the wort must be cooled to is once again dependent on the type of beer being brewed and the stand of yeast used. Yeast strains vary in their properties and the flavors they impact. The yeast is typically left in the fermentor for around 4 to 6 days or until the yeast consumes all of the sugars that were created during the malting process. The yeast metabolizes such sugars into ethyl alcohol, carbon dioxide, and heat. Because heat is produced, the fermented product must be cooled to around 30 degrees Fahrenheit (Briggs, et al., 2004). Cooling the product allows the yeast to settle to the bottom of the fermentor which allows for a better beer clarity and allows for the reuse of yeast in subsequent fermentations. Once fermentation is complete, the beer may be filtered or decanted and transferred to a “Bright Tank” (Trosset, 2018). This tank is where the beer is carbonated and kept until it is either kegged, bottled, or canned.

Although there are only four main step in brewing, the process is time intensive, taking up to six hours for the brewing process and generally 2 weeks for fermentation (Trosset, 2018), that varies from batch to batch. There are many components and factors that not only affect the quality of beer that are produced, but also the flavor and aroma of the product.

2.3 Hops

One component of the brewing process that greatly affects the finished beer product is the addition of hops. Hops are the cone-shaped flowers from *Humulus lupulus,* better known as the common hop plant. Hop cones contain a variety of acids, responsible for affecting the bitterness, and essential oils, which determine flavors and aromas. The infusion of hops add bitterness and/or aromas and flavors into beer, depending on the type of hop and when it is added during the brewing process.

Hops originated in the late eighteenth and early nineteenth centuries, during the height of the British empire (India Pale Ale, n.d). India, being one of Britain's more important outposts, had a climate too warm for brewing beer. Because of the increased demand for beer during this time, Britain needed to find a way to transport beer to India without it spoiling. To do this, George

Hodgson, a Londen Brewer, created a strong pale ale with hops and high alcohol contents to preserve the beer. This new style of beer came to be called the India Pale Ale, also known as an IPA. Today, IPAs serve as the most prominent and popular craft beer, accounting for 21% of volume share of the craft sector (Flaherty, 2016).

Within the cone-shaped flowers of the hop plants, there is a yellow, sticky powder called lupulin. The acids contained within the lupulin are called alpha acids, which are slowly converted to iso-alpha acids (IAAs) during the boiling stages of the brewing process. Iso-alpha acids are what give the beer its bitterness and also have antibacterial properties which prevent spoiling the beer. Prior to the transition to IAAs, alpha acids of different hops can contain different functional groups (such as, ketones, hydroxide, and alkenes) attached in many varieties. These variations are what give different levels of bitterness to beer. Unique flavors of beer can be attributed to many varieties of hops that have specific aromas.

Although less hops are used in the brewing process compared with water and malts, they contribute just as much to the final product. When adding hops to the beer, breweries rarely use the cones, as they are too bulky and difficult to process in automated equipment (Barth, 2013). Alternatively, hop pellets or hop extract are used. Hop pellets are made by drying out the hop cones, grinding them down into a powder, and pressing them into pellets. Using hop pellets is advantageous to brewers because they are smaller than the cones and can be used with automated equipment. When making hop extract, the cones are ground up and treated with either liquid or supercritical carbon dioxide. A thick oil remains after the carbon dioxide is released. The thick oil can then be added directly to the kettle of beer as hop extract (Barth, 2013). Using hop extract is also a preferable method because it creates a stronger hop flavor and there is no risk of insoluble, plant material entering the beer. In addition, the hop extract is easier to store and it has a longer shelf life.

Another factor that greatly affects whether the hops promote bitterness or flavor and aroma is the time at which the hops are added into the beer or wort. Hops that are added to the wort prior to boiling impart bitterness into the beer because the alpha acids are converted to the iso-alpha acids during the boiling phase. In this method, brewers will add the bitterness hops to the wort and boil for an hour to ninety minutes (Oladokun, 2017). This isomerization luckily results in low yields, therefore resulting in bearable levels of the iso-alpha-acids. To put it into perspective, the concentration in water is about 6 ppm, 15 ppm in a light beer, and up to 100 ppm in a very bitter IPA (Keukeleire, 2000). Because of the low yield, hops put in earlier in the wart boiling undergo more isomerization resulting in more iso-alpha-acids in the final product and a much more bitter taste, overriding the taste added by the hops. Hops that are used to influence the flavor and aroma of the beer can be 'late hopped'. This means that the brewers add the hop pellets or extract toward the end of the boil, to ensure that the essential oils are not boiled off.

This preservation of the oils results in the classic aromas of the beer, specifically IPAs. Another method of adding hops to affect the flavor and aroma is called dry hopping, which occurs post fermentation. This is because the isomerization does not occur, and therefore the hops only add flavor.

Throughout this project, we will be evaluating and analyzing five specific varieties of hops that Purgatory Brewing Company using in their brewing process. These include Citra, Mosaic, Vic Street, Centennial, and Galaxy. Citra is a American aroma hop, popular among craft brewers. It is known for giving beers citrus flavors, like grapefruit and lime, rather than used to introduce bitterness to the beers (Citra, 2018). Mosaic hops are used for infusing bitterness, flavor and aroma into the beers, giving a sense of primarily pine, mango, and blueberry (Mosaic, 2018). The third hop that Purgatory Beer Company utilizes is called Vic Secret, which gives lime and citrus aromas to the beer (Trillium Brewing Company, n.d.). Centennial hops, also known as Super Cascade, is versatile in that brewers use it to affect aroma and flavor . It is used commonly in Pale Ales and IPAs (Centennial, 2018). Lastly, the Galaxy hop is an Australian aroma hop, also used for Pale Ales and IPAs (Zach, 2018).

2.4 Beer Flavor

The characteristic element of beer, and what has trademarked it as a beverage around the world, is its flavor. Beer is composed of many different elements, each having its own impact on the final flavor. As defined by Charles Bamforth in *Beer: A Quality Perspective,* the main flavor of beer results from the interaction of malting and production processes with brewing raw materials (Bamforth, 2009). Each ingredient can affect the final taste of the beer in different ways, and it all starts from the raw materials used. The most important raw material used in brewing beer is the carbohydrates. This includes substances such as barley, hops, maize, wheat, and sorghum. In terms of flavor, hops provide the most influence among the carbohydrates (Bamforth, 2009). Different types of hops have differing individual flavors. In IPAs, hops are used in both specific quantity and type. This results in the characteristic ‘hoppy,’ fruity, and bitter tastes representative of the IPA. IPAs usually use many different hops and the combination of flavors characterise the brand.

The degradation of S-Methyl Methionine (SMM), an amino acid residue of barley proteins, to Dimethyl Sulfides (DMS), can also have an influential effect on flavor. This process results in the most significant flavor compound from the raw material of malted barley. Depending on the level of DMS produced, the final flavor can be more sweet or more earthy (Bamforth, 2009). This level can be high or low, but its resulting concentration is usually characteristic of different brands.

Aside from raw materials, compounds produced during the fermentation of the wort have a significant, even decisive effect on the final flavor (Bamforth, 2009). The main products produced during fermentation are ethanol and carbon dioxide, but other volatile products, principally esters, heavy alcohols, aldehydes, diacetyl, and sulfur compounds are produced. Esters are the most significant of the volatile products for flavor and thus require the most control to reproduce flavor. They impart fruity, floral, and solvent-like flavors. The most important esters are "ethyl acetate (solvent-like, fruity), isoamyl acetate (sweet, banana), isobutyl acetate (banana, fruity), ethyl caproate (apple), and 2-phenylethyl acetate (rose, honey)" (Boulton and Quain, 2006). The synthesis of esters during fermentation is not yet fully understood, but the resulting flavors and their impact is unquestionable.

In terms of higher alcohols, n-propanal, isobutanol, 2-methylbutanol, and 3-methylbutanol are the most influential for flavor (Boulton and Quain, 2006). These are more potent counterparts to ethanol and thus impart a more 'warming' and 'alcoholic' flavor to the beer. Interestingly, it has been studied that higher levels of 2-phenylethanol suppress the perception of DMS in the final beer from the malted barley (Bamforth, 2009). The formation of alcohols proceeds via the formation of aldehydes, though it is intriguing that aldehydes have a higher impact on flavor than their corresponding alcohols (Hughes and Baxter, 2001). The impact is not a positive one. The major aldehyde in beer, acetaldehyde, "confers an emulsion paint or green apple taste to beer" (Bamforth, 2009). Although not immediately significant, other aldehydes can be responsible for flavor taints in aging beer, usually due to higher alcohol oxidation (Hughes and Baxter, 2001).

The most negative flavors in beer come from sulfur containing compounds. Understandably, the most impactful sulfur containing compound, due to its creation during the process, is DMS (Bamforth, 2009). Thus, the majority of the sulfur containing compounds are created during the oxidation of SMM. These compounds are not desirable in beer unless their levels are strictly controlled. The table below shows the important compounds containing sulfur and the flavors associated with them (Bamforth, 2009).

Table 1*: Flavor descriptors of common sulfur-containing compounds*

Class	Examples	Flavour descriptors
Inorganic	Hydrogen sulfide Sulfur dioxide	Rotten eggs Struck match
Thiols	Methanethiol 3-Methyl-2-butene-1-thiol	Putrefaction Lightstruck, "skunky"
Sulfides	Dimethyl sulfide	Sweetcorn
Disulfides	Dimethyl disulfide	Rotten vegetable
Trisulfides	Dimethyl trisulfide	Rotten vegetable, onion
Thioesters	Ethyl thioacetate	Cabbage

2.5 Beer Aroma

While flavor may be the most important aspect of the overall impression of a beer, beer aroma can greatly sway what the palate will soon taste (Teku Tavern, 2017). The different aromas of beer are caused by the addition of aroma hops towards the end of the kettle boil (Boulton, 2013). The scent of the beer and the intensity of the beer scent are caused by certain volatile compounds within the beer. These volatile compounds can be determined using a variety of gas chromatography – olefactory (GC-O) experiments (Grosch, 2001).

Once the volatile compounds are determined through GC-O, the concentrations of the compound at the odor threshold, also known as the Odor Activity Values (OAVs), can be found. Typically, compounds with higher OAV values are the compounds most necessary for the aroma, however there are exceptions where compounds with lower OAV values contribute to the aroma as well. Therefore, experiments must be performed to determine which compounds are necessary to the overall aroma (Grosch, 2001).

The aroma of beer can be categorized into five main characteristics – green, citrus, spicy, floral, and muscat. Green scents are similar to the odor present in green leaves, citrus scents are reminiscent of lemons or oranges, spicy scents are similar to nutmeg or cinnamon, floral scents smell like fragrant flowers, and muscat scents are similar to the smell of grapes and peaches. Scents of different beers are typically categorized by a trained panel.

When different volatiles are present in the same mixture, they can interact and bring forth a new scent altogether. For example, in a study done by Kishimoto et al. (2008), Green odorants were observed for (Z)-3-hexen-1-ol, and Muscat odorants were observed for 4-MMP, (Z)-3-hexen-1-ol, and a compound that the researchers could not quantify since the result was too weak to be definitively identified by GC-O. The different combination of volatiles led to different overall aroma categorization (Kishimoto et al., 2008 and Kishimoto et al., 2006).

The intensity of beer aroma is another factor to consider when testing different types of beers. According to a study by Vollmer and Shellhammer (2016), the intensity of beer aroma typically depends on the hop oil quality and hop oil composition. The quality and composition of hop oils can vary within one type of hop due to differences in location, climate, irrigation, and disease pressure. Hop oil quality and composition can also change due to post-harvest process, storage, transport, and evaporation. The intensity of beer aroma is also typically quantified using a trained panel (Vollmer & Shellhammer, 2016).

2.6 Analyzing Beer Quality

On a high level, beer is a relatively simple mixture consisting mostly of water, ethanol, and carbon dioxide. These three components make up the vast majority of the popular beverage, and are well understood within the scientific community. However, without the last small percentage of carbohydrates and proteins, beer would have no identity or signature taste. Understanding this small but critical portion of beer has been the task of many hoping to identify specific molecules that make the beverage worth drinking - or not.

Analyzing and determining the various components of a certain beer can indicate the quality of the drink. For example, as mentioned previously, high amounts of sulfur compounds would indicate that the brewing process went wrong at some point and will likely result in an unpleasant odor and taste. To determine if these and other compounds are present, two common laboratory methods used are gas chromatography (GC) and high performance liquid chromatography (HPLC). Though differing slightly in their methods, both GC and HPLC effectively separate compounds within a mixture and output results detailing the various components. The differences lie in the phases in which each method analyzes the mixture. GC, as its name implies, analyzes and separates the mixture while in gas phase. For this reason, GC is used in conjunction with volatile compounds, compounds that are responsible for aroma, and can point to molecules that are responsible for a beer’s certain smell. HPLC, on the other hand, separates the mixture while in liquid phase. Most HPLC machines prefer to analyze non-ionic compounds, so beer (an aqueous solution) is usually mixed with a solute such as methylene chloride to extract the organic compounds and not damage the machine. Both GC and HPLC offer insight into specific molecules that are present in the sample.

While it is useful to recognize the specific compounds present in beer, it has proven difficult to determine precisely which compounds are responsible for certain flavors. Within a sample of beer, there are likely hundreds, if not thousands, of different compounds working together to give the drink its specific flavor, and therefore it is also useful to look at additional methods of determining beer quality. Some factors that brewers often consider are beer clarity, color, percent alcohol, pH, and overall taste and aroma.

Beer clarity and color are two factors that often go hand-in-hand and can offer the consumer insight to their first impression of the drink. Light travels through beer at various wavelengths, depending on the color of the beer and the amount of undissolved particles, often hops, within the liquid. A common method of determining the color and clarity is through the use of spectrophotometry, where light of a specific wavelength is passed through a sample. A percentage of this is absorbed by the sample, which can be compared to a reference to determine the variables of interest (Barth, 2013). The Standard Reference Method, or SRM, is one reference commonly used to determine the color of beer based off of the specific absorbance of the sample (Barth, 2013).

Percent alcohol is another important consideration for brewers and consumers alike. Though alcohol content varies from one beer type to another, beer typically contains anywhere from four to twelve percent alcohol (Hughes, 2007). An unintended percentage above or below this range will likely throw off the flavor profile and mask other important flavors that are present. Most commonly, the ABV (percent alcohol by volume) is found through a hydrometer, which measures the beer's specific gravity (Barth, 2013). To find ABV, brewers can measure the specific gravity of both the non-fermented and fermented beer and then estimate the ABV from a table.

Similarly to measuring the ABV of beer, pH is another factor that is simple and straightforward to measure, but critical for a beer's taste and quality. pH indicators, substances that change color when introduced to different values of pH, or pH probes are common methods in determining the relative acidity of beer. An advantage of using pH paper is that one drop of the sample is sufficient. However, this comes at the cost of accuracy, a criteria where pH meters tend to excel. For beer, optimal pH generally lies between values of 3.7 and 4.4. Below this range, metallic after palate tastes have been recorded, while "soapy and caustic notes" have been reported at pH above this range (Gijs, 2002).

While clarity, color, percent alcohol, and pH give brewers and consumers valuable insight into the overall quality of the beer, the most trusted and commonly used method is also the most simple: tasting the beer. Practiced tasters, people who have trained their tongue and nose to identify specific flavors and aromas can give insightful feedback that technology sometimes can't. Using common terminology from "hoppy" (giving a hop aroma, not including bitterness), to "vinous" (reminiscent of wine), and even "estery" (floral aroma or flavor), tasters can qualitatively describe the complex mixture of carbohydrates and proteins in the beer in the form of a flavor profile ("Beer and Brewing Terminology," n.d.). This method is straightforward, cost effective, and also replicable, which is why many brewers elect to use it to determine beer quality. In fact, from a study done in 1979 by J.F. Clapperton, a member of the Brewing Research Foundation, training and experience with beer taste testing were shown to increase reproducibility and discrimination when using a flavor profiling system. Though qualitative, with proper training and practice, taste testing panels have been proven effective and are valuable tools in analyzing tastes and aromas when it comes to evaluating a substance as complex as beer.

3. Methodology

The goal of this project was to develop a new beer product for Purgatory Beer Co. using different combinations and concentrations of hops. Additionally, this project was aimed to chemically analyze the flavors, aroma, and chemical structure produced when using different combinations of hops in the same beer base. The following are objectives that were created to assist in completion with these goals:

1. Determine the sponsor's optimal flavor, dry hop different quantities and combinations of hops using Bud Light.
2. Analyze the sponsor's lowest and highest ranked beer flavors using GC-MS and IR Spectroscopy to determine any chemicals associated with flavors.
3. Determine the sponsor's optimal hop flavor using Purgatory Beer Co.'s beer by changing hop concentrations of the highest scored beers from the flavor test in Objective 1.
4. Analyze the sponsor's highest ranked beer flavors using GC-MS, pH, and specific gravity to determine chemical patterns associated with sponsor's optimal flavors.

3.1 Objective 1: Determine Optimal Flavor Combinations of Hops using Bud Light

To maximize our tests with Purgatory Beer's wort, we decided to first run tests on Bud Light to predict the final flavor. Using the best rated hop combinations, we could then run tests on their wort to judge the similarities and hopefully augmented flavor. We were primarily concerned with 5 differing hops as these were the most commonly used ones in the brewery. These five were: Centennial, Citra, Galaxy, Mosaic, and Vic Secret.

3.1.1 Determining Combination Trials to Test

We decided to test combinations of single concentrations, double combinations, and triple combinations. The following table shows our selection matrix for two combinations:

Table 2: *The selection matrix for combinations of two hops. The 'X' represents tests we carried out and the blanks are repeats.*

	Citra	Mosaic	Vic Street	Centennial	Galaxy
Citra	X	X	X	X	X
Mosaic		X	X	X	X
Vic Street			X	X	X
Centennial				X	X
Galaxy					X

By eliminating repeats as the order of combination does not affect the final flavor, we ran 15 ests. The red 'X's were kept as a basic trial for testing a doubled concentration.

Next, we choose to test combinations of three unique hops which can be seen below:

- M-Ce-Ci
- M-G-Ci
- G-Ci-VS
- M-G-VS
- M-Ci-VS
- G-Ce-Ci
- M-Ce-VS
- Ce-Ci-VS
- G-Ce-VS
- M-G-Ce

3.1.2 Dry Hopping Procedure

After determining the trials we would run tests on, we ran the trials on Bud Light. We chose Bud Light as a plain and cost effective beer so we could see the maximum effects of the hops on the beer quality. To test and verify our methodology worked, we first experimented with an initial batch of 5 containing just single hops of 1 gram. Our methodology for dry hopping was as follows:

1. Acquire Bud Light bottles with twist off caps
2. Select combination of hops for test
3. Weigh out each hop of desired quantity on a scale making sure the floor does not quake
4. Add combination of hops into tea bag and tie shut
5. Open Bud Light bottle
6. Insert tea bag into bottle pushing down to make sure fully submerged
7. Seal bottle
8. Refrigerate for 5-8 days

It was important to seal the bottles completely after the hop additions so the least amount of carbonation is lost and flavor is preserved. After the refrigeration period we brought our trials in their sealed containers to Purgatory Beer to be analyzed by a tasting panel. The procedure for that can be seen in the next section below.

3.1.3 Taste Testing Panel

To qualitatively analyze the quality of each of the dry hopped beers, we performed a taste test. The scorecard that was used was taken directly from the Beer Judge Certification Program, and can be found in Appendix X (Evaluating Beer: Tasting and Judging For Style). The steps taken for the taste testing panel are as follows:

1. Randomize samples so testing panel is unaware of combination identity by numbering each sample
2. Present random sample to panel for testing
3. Hand out beer scorecards (Appendix A) with accompanying definitions
4. Have panel fill out individual scorecards for each test sample
5. Use sample number to identify beer and input scorecard results

Our sponsor tasted and scored each beer individually, allowing us to develop a hierarchy of dry hop combinations to analyze for further testing.

3.2 Analyze the Sponsor's Lowest and Highest Ranked Beer Favors Using GC-MS and IR Spectrum

In attempt to relate beer flavor to chemical composition, our group ran tests on a variety of beers hopped in section 3.1. We initially ran the tests using each of the single hops (5 beers total) to be used for a basis for beers containing multiple hops. We analyzed the top three and bottom three scored beers containing two hops along with the top two and bottom two scored beers containing three hops. The two tests that we ran for our initial testing was Gas Chromatography Mass Spectrometry (GC-MS) and Infrared (IR) Spectroscopy.

3.2.1 Setting Up Samples for GC-MS

Our group decided to use GC-MS as an initial test method for our samples due to the ability to identify different substances within a test sample. When preparing samples to be run within the GC-MS, only organic material can be read through the spectrometry instrumentation. To ensure all of the water within our samples are removed prior to loading to the instrumentation, our group first adds dichloromethane (DCM) to our beer samples. After centrifuging each sample containing DCM we transferred only the organic phase of the beer sample to filter vials containing a calcium chloride rock to absorb any remaining water. The samples are then run through the GC-MS. After the samples are run through the GC-MS instrument, our group will identify which substances most closely are present in each beer sample examined through peak analysis. Our group will prepare and run samples for each dry hopped beer described in section 3.2.

3.2.2 Setting Up Samples for IR spectrum

Our group used IR spectroscopy as a secondary testing method for our samples. Similarly to GC-MS, IR spectroscopy can identify different organic compounds present in our samples. We ran IR spectroscopy for the dry-hopped beers described in section 3.2. Our preparation of samples was similar to GC-MS sample preparation. We first added DCM to our beer samples, then centrifuged each sample, and then transferred the samples into filter vials and added calcium chloride to absorb the remaining water. When running the samples, the IR spectrometer was cleaned with acetone and a kimwipe, and the sample was pipetted into the IR spectrometer. The spectrometer was cleaned in between running each sample. Our IR spectroscopy results will be compared to one another to identify volatiles present in our sponsor's favorite and least favorite beers.

3.3 Determine the sponsor's optimal hop flavor using Purgatory Beer Co.'s Beer

The next phase of this project was to test different combinations of hops on Purgatory Beer Co.'s beer. After acquiring Purgatory's fermented IPA right before it was dry-hopped, we transported the fermented IPA to our lab in a sealed 5-gallon bucket. We distributed it into masons jars with twistable lids. To determine which of the hop combinations we would test, we reviewed the top scoring combinations from the results of objective 2. The top five combinations using two hops and the top two of combinations consisting of three hops were chosen to test. Another variable was introduced at this stage: quantity of hops within the beer. We decided to increase the amount of hops added, to determine what effect, if any, that would have on the beer. We also wanted to vary the concentrations of hops within these combinations, to see how ratio of multiple hop affects the beer. For example, the centennial hop is typically used to increase bitterness of beer, rather than affect flavor. Therefore to alter the flavor of the beer more, we decreased the amount of centennial hop, while increasing the citra hop. All of the tested combinations of hops with their respective quantities are listed below.

- 4 Grams Citra
- 2 Grams Citra
- 4 Grams Mosaic
- 2 Grams Mosaic
- 1 Gram Citra/ 1 Gram Centennial
- 2 Grams Citra/ 1 Gram Centennial
- 1 Gram Mosaic /1 Gram Centennial
- 2 Gram Mosaic/ 1 Gram Centennial
- 1 Gram Mosaic/ 1 Gram Galaxy
- 2 Gram Mosaic/ 1 Gram Galaxy

The procedure for dry hopping these beers was the same as in Section 3.2.1 above, however in these trials, mason jars were used to hold the beer. Since Purgatory's fermented IPA still had yeast in it, the production of CO_2 caused the mason jars to become pressurized, so the tops of the mason jars were opened daily to avoid explosion. After being refrigerated for five days, the quality of each of the dry-hopped beer was analyzed by the same testing panel using the same procedure as previously described in Section 3.1.3. This analysis allowed us to quantitatively rank each beer and determine the top flavor combinations.

3.4 Analyze the sponsor's highest ranked beer flavors using GC-MS, IR Spectrum, pH, and specific gravity to determine chemical patterns associated with sponsor's optimal flavors

After determining the top flavor combinations from the taste testing panel, we quantitatively analyzed each beer using GC-MS and IR spectrum. These tests allowed us to associate chemical patterns and molecules in the samples with a higher quality beer. We followed the same procedure for GC-MS and IR spectrum as described above in sections 3.2.1 and 3.2.2 above, respectively. SG and pH are common indicators of beer quality and were tools to give us further insight into the quality of our beer. For both tests, we separated the beer samples into labeled aliquots and loaded into a pH meter to test for pH, and a hydrometer to test the specific gravity.

4. Results and Discussion

After testing, we had much raw data to work with. We looked at this data and attempted to find correlations and links between the chemical compounds we found and the resulting scores of the beer. Our full analysis between each trials and method we used to test the beers can be found below.

4.1 Beer Taste Test Results

To quantify the quality of the beer, we used the scorecard and panel testing procedure detailed above in the methodology. We first used this method to find good combinations of hops in Bud Light. From this data, we then applied this knowledge to Purgatory's wort to see the transition. A thorough examination of this data can be seen below.

4.1.1 Bud Light Taste Test Results

The first round of taste testing that was conducted was using combinations of the five hops in Bud Light. The goal of this was to determine the top combinations that the project sponsor preferred, using a bland, plain beer base. Table 3 below displays each combination with corresponding flavor descriptions reported from the project sponsor. The overall scores are in the right column, with the highest, and most favored, combination at the top.

Table 3: *Results from taste tasting hop combinations of two in Bud Light, including noted flavor descriptions and overall calculated scores*

Hop Combination	Flavor Descriptions	Overall Score
Ci-Ci	sweet, fruity, subtle, not bitter, extra fruit at end	76
Ci-Ce	sweet, no aftertaste, subtle, stays smooth	70
M-G	fruity, citrus, bitter on back end	69
M-Ce	sweet, fruit, mild intensity, smooth, sweet to bitter at end	59
M-M	fruity, yet subtle	59
VS-G	malty, caramel, earthy, mild intensity, consistent, pine	53
G-G	mild, not bitter, malty, subtle, tart	50
Ci-M	very smooth, mild, subtle, bready, no fruit	40
Ce-G	little bitter, malty, mild intensity	40
VS-Ce	bad aftertaste, malty, earthy	31
Ci-G	very mild, subtle, bland	31
VS-VS	little bit of banana, sour	24
Ci-VS	malty, piney, bitter, earthy, woodsy	24
Ce-Ce	very bitter, bad aftertaste, sulfur, malty	17
M-VS	very strong, bad aftertaste, bitter, earthy, harsh	17

From the table above, it can be noted that combinations containing certain hops generally result in good or bad overall scores, depending on the hop. For example, five out the the bottom six overall scores are combinations containing Vic Secret. This suggests that our project sponsor did not favor the Vic Secret hop in the beer combinations. On the contrary, Citra is found in the top two overall scores, and Mosaic is found in three of the top five combinations, suggesting those are two of the preferable hops.

The next round of taste testing included combinations of three different hops in Bud Light. The results are displayed in Table 4 below.

Table 4: *Results from taste tasting hop combinations of three in Bud Light, including noted flavor descriptions and overall calculated scores*

Hop Combination	Flavor Descriptions	Overall Score
M-G-Ce	sweet, fruity, smooth, consistent	87
G-Ce-Ci	smooth, turns thin on the back end	76
M-G-Ci	sour but fruity, balanced, a little bit tart	60
G-Ce-VS	pretty smooth, woodys, subtle	56
M-Ce-Ci	fruity, but also harsh, sweet	47
Ce-Ci-VS	sweet, dissipates to reveal bitter and chalky	44
M-Ci-VS	bitter, bready, intense, gets worse	23
G-Ci-VS	Super bitter, intense, harsh, little of caramel	22
M-Ce-VS	bitter, bready, piney, intense	22
M-G-VS	bad aftertaste, dirty on back end, ginger	16

The conclusion made above regarding the dislike of Vic Secret still holds true when looking at the table above. Vic Secret is present in the bottom five hop combinations.

4.1.2 Purgatory Beer Taste Test Results

Using the results of our Bud Light taste tests, we dry hopped the top five combinations of two hops using Purgatory's beer base. We dry hopped the two hop combinations at their original concentration as a control variable. To determine whether concentration affected the overall impression of the beer, we increased the concentration of one of the hops. We increased the concentration of the hop that had a higher score in the Bud Light taste tests - for example, in the combination Mosaic/Centennial, we doubled the concentration of Mosaic, since it had a Bud Light taste test score of 59 and Centennial had a score of 17. The graph below shows the taste test results for combinations of two hops in Purgatory's beer base.

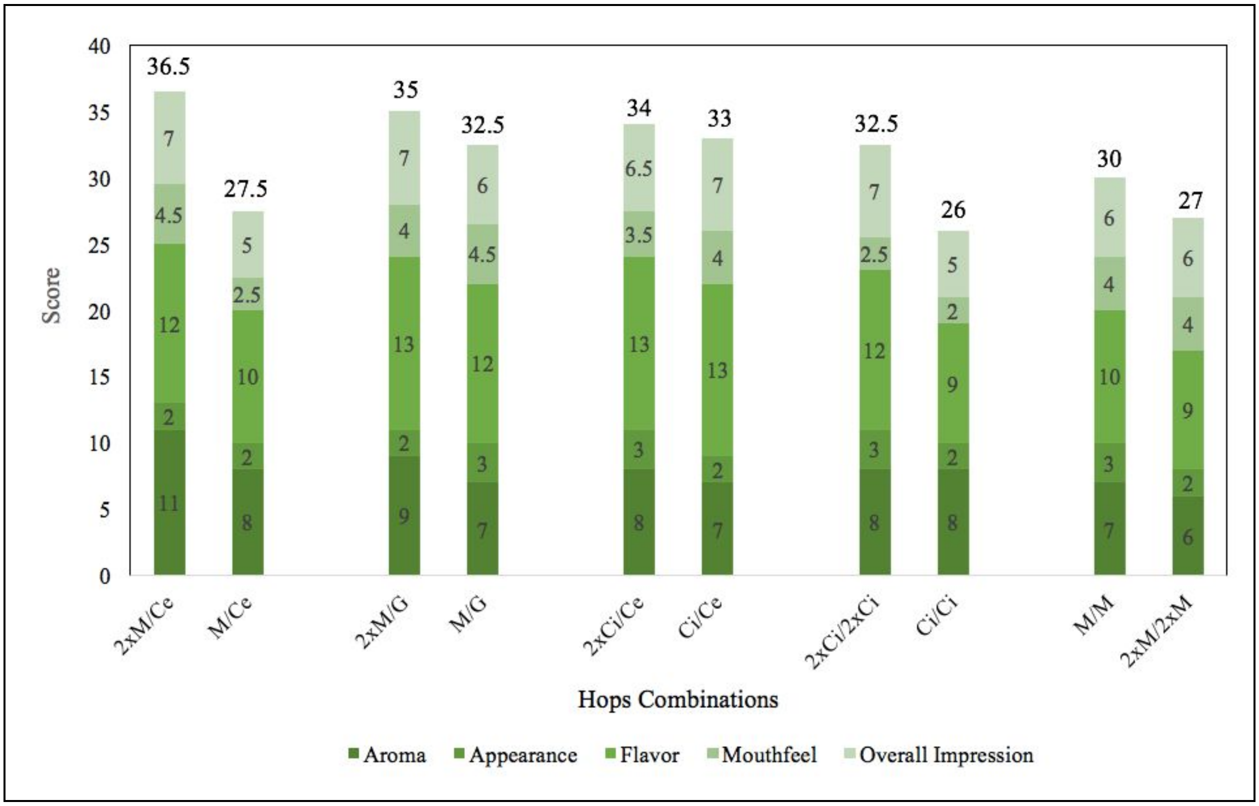

***Figure 2**: Taste test results from combinations of two hops in Purgatory's beer base, varying concentration*

Generally, the beers with a higher concentration of one hop were awarded higher overall scores than the beers that were dry hopped at their original concentration. Both the appearance and mouthfeel scores did not have any general trends with the change in concentration. The aroma score for the increased concentration of hops was consistently higher than the original concentration of hops. For different combination of two hops, the aroma descriptions of the original concentration and the varied concentration were typically somewhat similar - for example, Double Citra / Centennial was described as "fruity, orange" and Citra / Centennial was described as "tangerine". The use of similar aroma descriptor words indicates that the original concentration and the higher concentration have similar aromas. Generally, the flavor score also increased when the concentration of the hops was increased. The flavors of the original concentration and the higher concentration were described using very different words, indicating that the flavor of the beer changed with the change in concentration.

After taste testing combinations of two hops dry hopped in the Purgatory beer base, we selected the top three combinations of three hops from the Bud Light taste test results to dry hop in the Purgatory Beer Base. Following a similar procedure to the combinations of two beers, we increased the concentration of the two highest scoring hops out of the combination of three - for example, in the combination Galaxy / Citra / Centennial, we increased Galaxy and Citra, since they had scores of 50 and 76 respectively and Centennial had the lowest score of 17. We also varied the concentrations of the two higher scoring combinations of three, and did not vary the lower scoring combination of Mosaic / Galaxy / Citra. The graph below shows the combinations of three hopped in Purgatory's beer.

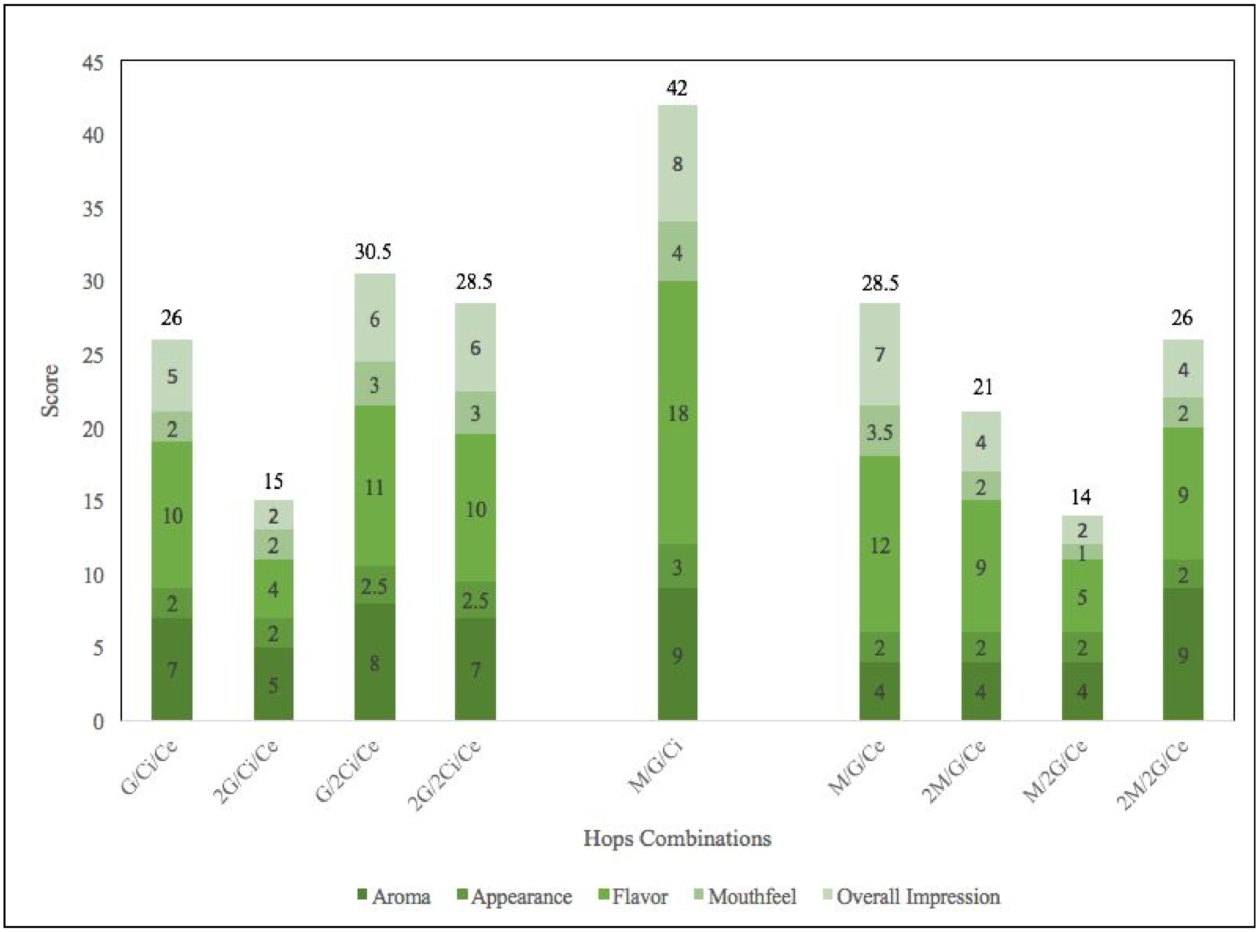

Figure 3: *Taste test results from combinations of three hops in Purgatory's beer base, varying concentration.*

Both of the beers that had an increased concentration of Galaxy were rated the lowest overall. The flavor scores of these beers were significantly lower than the rest of the beers that were taste tested. The flavor of the beers with a higher Galaxy concentration was described as "bitter". This aligned with our predictions, since Galaxy was the lowest scoring individual hop during the Bud Light taste tests. Additionally, the lowest scoring combination of three hops from the Bud Light test, Mosaic / Galaxy / Citra, scored the highest our the taste test using Purgatory's beer. In both the Bud Light taste test and the Purgatory Beer taste test, the flavor of this combination of three hops was described as "balanced", "sweet", and "fruity", and the flavor scores were relatively high in comparison with the other beers that were taste tested that day. During the Bud Light tests, he aroma score for this hop combination was the lowest score possible and the aroma was described as “skunky”. However, during the Purgatory Beer test, the aroma was rated the highest in comparison with the other beers tested that day, and the aroma was described as “caramel” and “sweet”. Few other beers had this large of a difference in score between the Bud Light taste tests and the Purgatory Beer taste tests, so the low aroma score may have just been a misperception made by the taste-testing panel.

After looking at the differences between hop combinations of two and three, we wanted to understand which hops produced the best flavors. To quantitatively understand if there was a trend that could be seen, we added and then averaged the overall scores for each of five hops to create a weighted percentage. Because not all five hops were used with our sponsors wort, we did this analysis based off the Bud Light overall scores. We ended up having an five different overall scores to weight for the Bud Light hop combinations of two and six different overall scores to weight for the Bud Light hop combinations of three. Since the testing of Bud Light was performed over two different days (one for combinations of two and one for combinations of three) we kept those averages separate since they are subjective. The results can be seen below where the weighted averages of combinations of two are on top of the arrow and combinations of three are below the arrow.

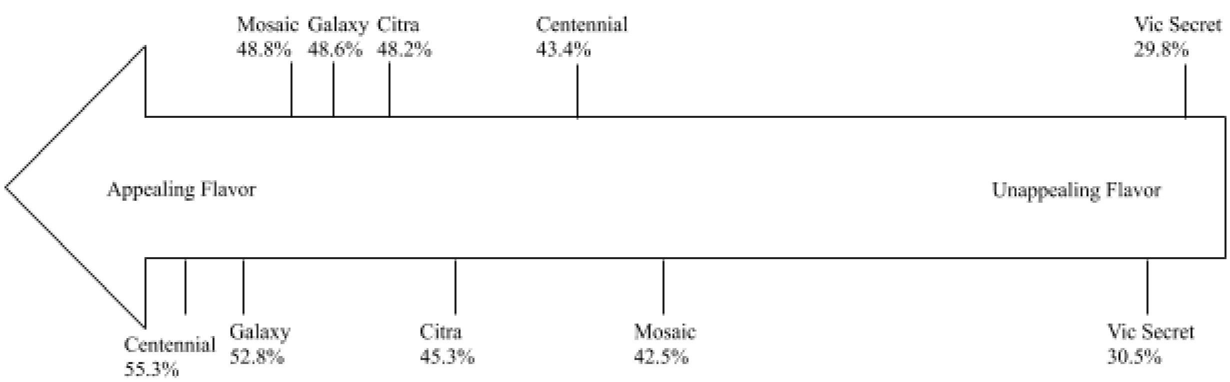

Figure 4: *Individual hop flavor trends produced from weighted scores of hop combinations*

As seen in the figure above, there are many trends that were seen by creating a weighted score for each hop. In both the combinations of two and three, Vic Secret created the lowest score by over 10%. Based off the descriptions from the beers containing Vis Secret, the low score of this hop was not very surprising to our group. When looking solely at the combinations of two scores, Mosaic, Galaxy and Citra all produced very similar weighted averages. Additionally, when looking at the Bud Light only containing one kind of hop, as seen in Table 3, the beers were scored in the order of Citra, Mosaic, followed by Galaxy. It was interesting for our group to see that although the Bud Light only containing Citra was the highest scored beer, on average the combinations containing Mosaic and Galaxy produced a higher score than Citra. Centennial scored an overall lower score than the previously discussed hops, but still had a much higher average than Vic Secret when looking at combinations of two.

While looking at the trends seen in the weighted averages of three hop combinations in Bud Light, there were very different trends observed. Centennial, which produced the fourth best flavor from the combinations of two, scored the best flavor for the combinations of three. Galaxy closely followed Centennial and again was scored as the second most flavorful hop. Mosaic, score a lower score in the combinations of three analysis and became the fourth most flavorful hop compared to the first as previously mentioned. One thing to note with the results from these tests is that the panel scored the combinations of three much higher than combinations of two. But again, because these beers were tested on different days, it is hard to compare the numbers due to subjectivity.

From analyzing this figure, it can be seen that hop flavors can change based off the different types and amounts of hops that are added to a beer. This trend was seen when comparing beer containing only one hop to beer with two and three combinations of hops. The following information can be utilized to understand how flavor changes and which combinations will produce the most flavorful results.

4.2 Compound Analysis

4.2.1 GC-MS Results Analysis

The beer taste tests gave us a qualitative window into the quality of the beer, but to obtain a more in depth understanding of the factors impacting the beer's quality we ran the samples through GC-MS. The data outputted from the GC-MS gave us some insight into specific compounds present in the sample, showing us what was occurring at a molecular level and differences between the different hop combinations. An example of a GC-MS output for the Citra and Vic Secret combination is shown below:

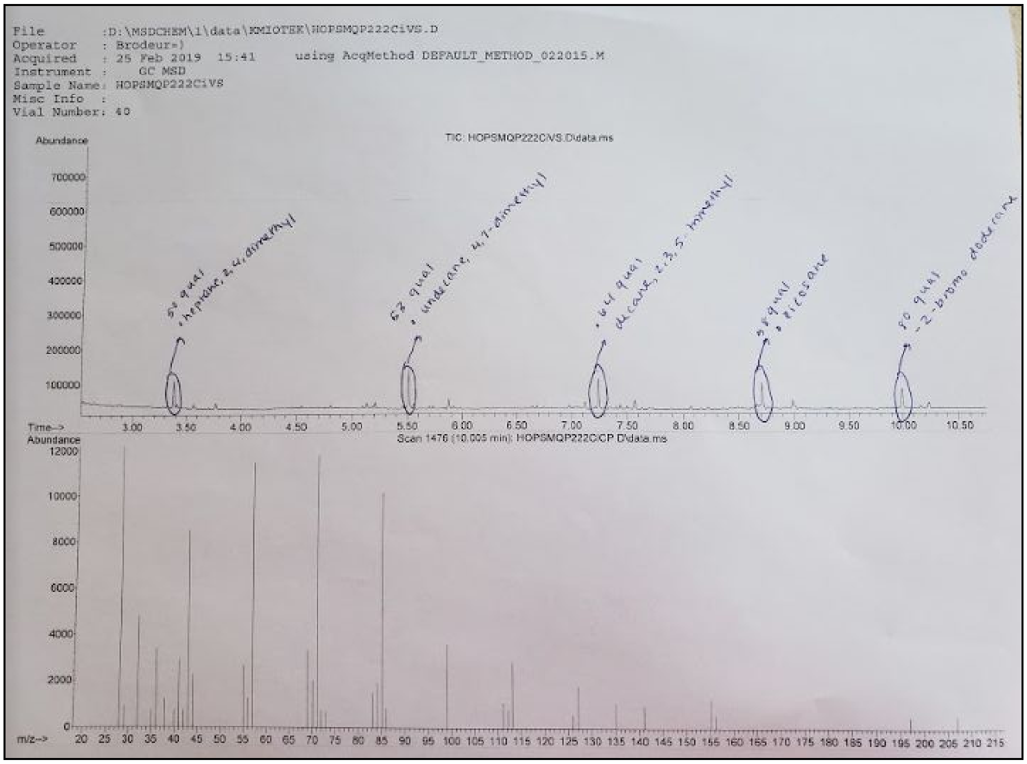

Figure 5: *GC-MS results for sample dry hopped with Citra and Vic Secret*

The outputted data displayed the relative abundance and atomic weights of the compounds that were determined to be present in the sample. The "quality" of the compound was also determined via GC-MS, representing the percent match of the compound found in the sample to that of the pure compound run through the apparatus. In analyzing the data, we made the decision to use the information from peaks two through five, as the first peak was the same across all samples and the last peak tended to have very low absorbances and qualities, consequently giving us a low level of confidence in the data from that peak.

After matching the peaks to their respective compounds, it was apparent that though all of the samples consisted of one of two of the same bases (Bud Light or our sponsor's wort), the identity of the compounds within each varied considerably (the comprehensive list of GC-MS results can be found in Appendix C). Consequently, we decided to examine trends between compounds within the sample and a resulting good or bad beer, as well as trends between compounds and specific flavors imparted into the beer during the dry hopping process. First, we ran an analysis to examine the trend between compounds and the overall quality of the beer. Relative quality was simply broken into two categories of "good" and "bad," determined from taste tests with our sponsor where there was a natural break in the overall scores. For the Bud Light samples, we determined an overall score of 50 as the cutoff between good and bad, and similarly a score of 60 for our sponsor's beer samples. For example, the Mosaic/Galaxy Bud Light dry hop sample that scored a 69 was considered as a good beer. Once all samples were appropriately categorized, we identified compounds that were common across multiple samples and denoted whether they were a potential contributing factor to either the good or bad flavors. Additionally, since none of the matches from GC-MS were perfect, we factored in the quality of the match to give each compound a score. More details and the complete results of these calculations can be found in Appendix F.

After determining the compounds that appeared across multiple samples and assigning scores to each, we produced the Figure 6 below.

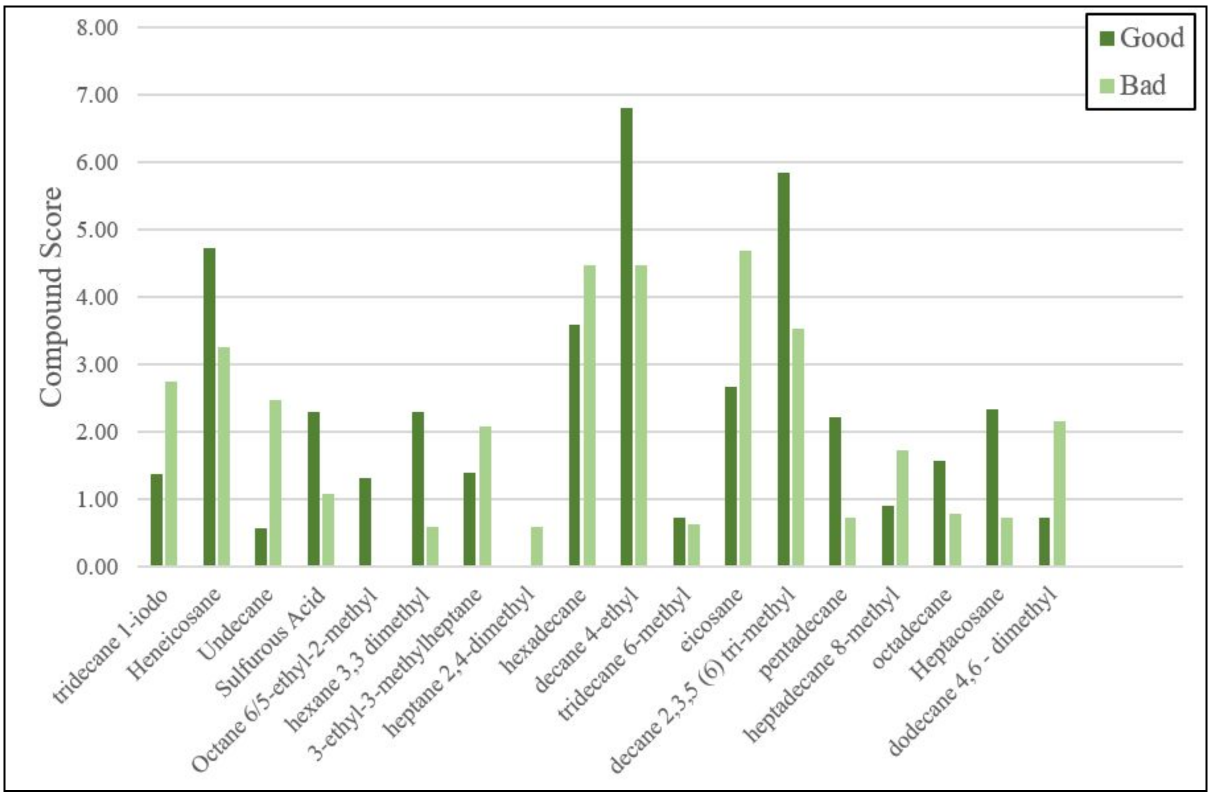

Figure 6: *Compounds detected in beer samples sorted by appearance in "good" versus "bad" samples*

As is evident in the figure above, a number of compounds appeared in both good and bad beer samples, pointing to the likely possibility that such compounds were present in the beer bases. Various forms of decane, for example, such as decane 2,3,5 tri-methyl and decane 4-ethyl are present in various forms of food, and some evidence even points to the compound as a component of pine (Decane, 2019). The hops that we worked with often contribute a "piney" flavor to the beer, so this compound could be a factor there. On the other hand, some compounds tended to appear more in either good or bad flavored samples. We filtered the data to include such compounds, where the molecule appeared in double the amount of good samples as bad, or vice versa, to produce the following figure:

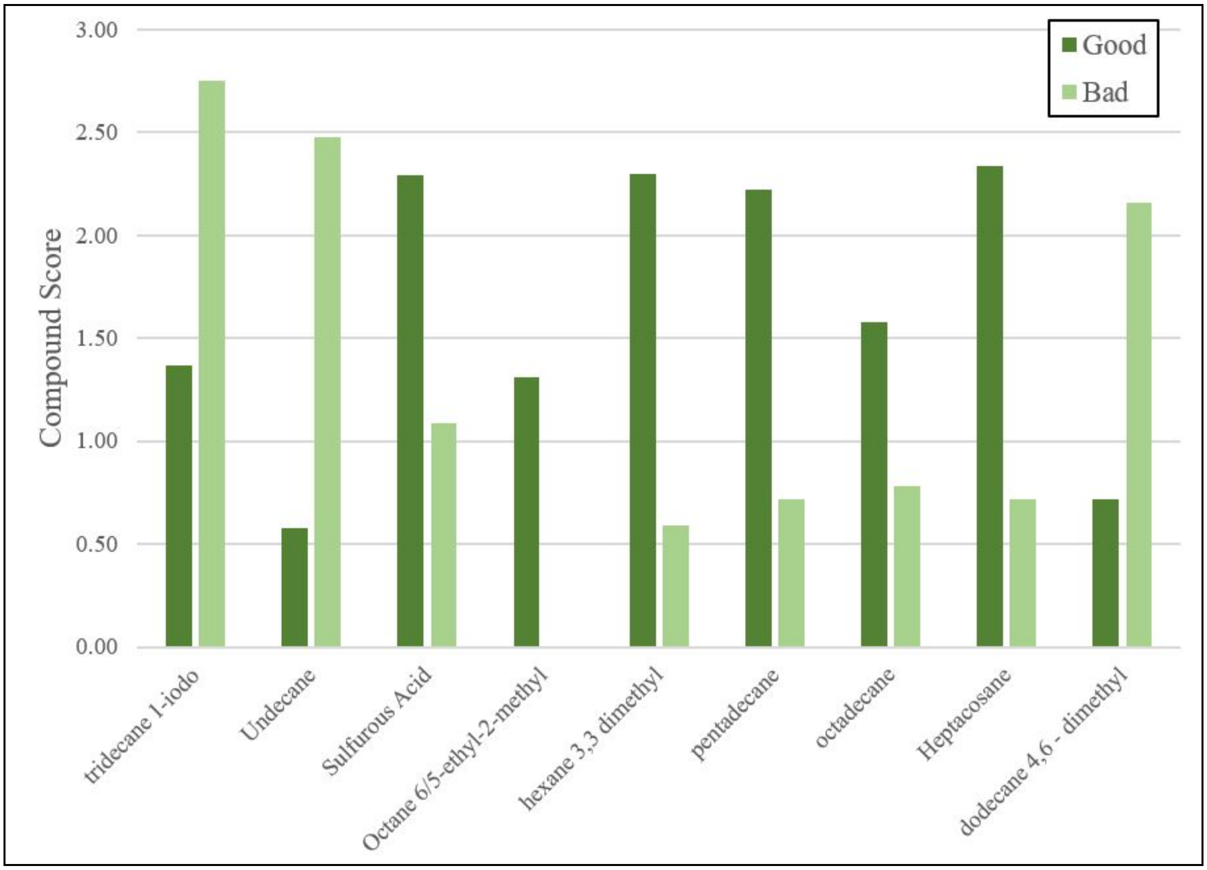

Figure 7: *Compounds that appeared in 2x more good samples than bad, or vice versa*

Some notable compounds from this list that have been found in food include pentadecane, octadecane, and undecane. Pentadecane has been identified as a component of volatile oils from plant species, and octadecane has been found in hop oil (Pentadecane, Octadecane 2019). Both of these compounds appeared more so in beer samples with "good" flavors and are also components of either major aroma or flavor contributors, increasing the likelihood that these compounds are in fact beneficial towards beer flavor. On the other hand, undecane was found more commonly in beer samples that were not as accommodating to the taste buds. Undecane has been identified as allspice, fried chicken, and fried bacon, among other foods (Undecane 2017). The trend with this compound is not as clear; in theory fried chicken or bacon flavored beer does not come across as appealing, but allspice on the other hand could add an interesting component to the drink. The trend from our data seems clear as undecane being a component that is best avoided, but the reasons why could be researched more deeply.

Regarding the remaining six compounds, little was published about more complex compounds in food, such as compounds with unique or multiple functional groups. Therefore, these compounds could be used as indicators to the quality of the beer upon GC-MS testing and identification, but on their own they can not provide as much substance with specific flavors that would be contributed to the beer. Last, sulfurous acid was a compound that literature repeatedly suggests causes a decline in the quality of drink flavor. The fact that our data shows it being a beneficial compound could mean that sulfurous acid was present in multiple beers, but not in levels that were detectable by taste. However, it also is a reminder of the subjectivity of the taste tests that we ran - the taste tests were over multiple days and at different times, all possible contributors to differences in scores from day to day.

4.2.2 IR Spectrometry Analysis

Another method of analyzing the functional groups found in the beer is through infrared (IR) spectroscopy. After taste testing the hop combinations in the bud light, we decided to run the samples through the IR spectrometer to determine the chemical composition. Unfortunately, the graphs obtained from the IR spectrometer were not as we expected, and did not aid in the analysis of the hop composition. For example, we ran the Bud Light with Vic Secret twice, and two completely different graphs were generated, as shown in Figure 8 and 9 below.

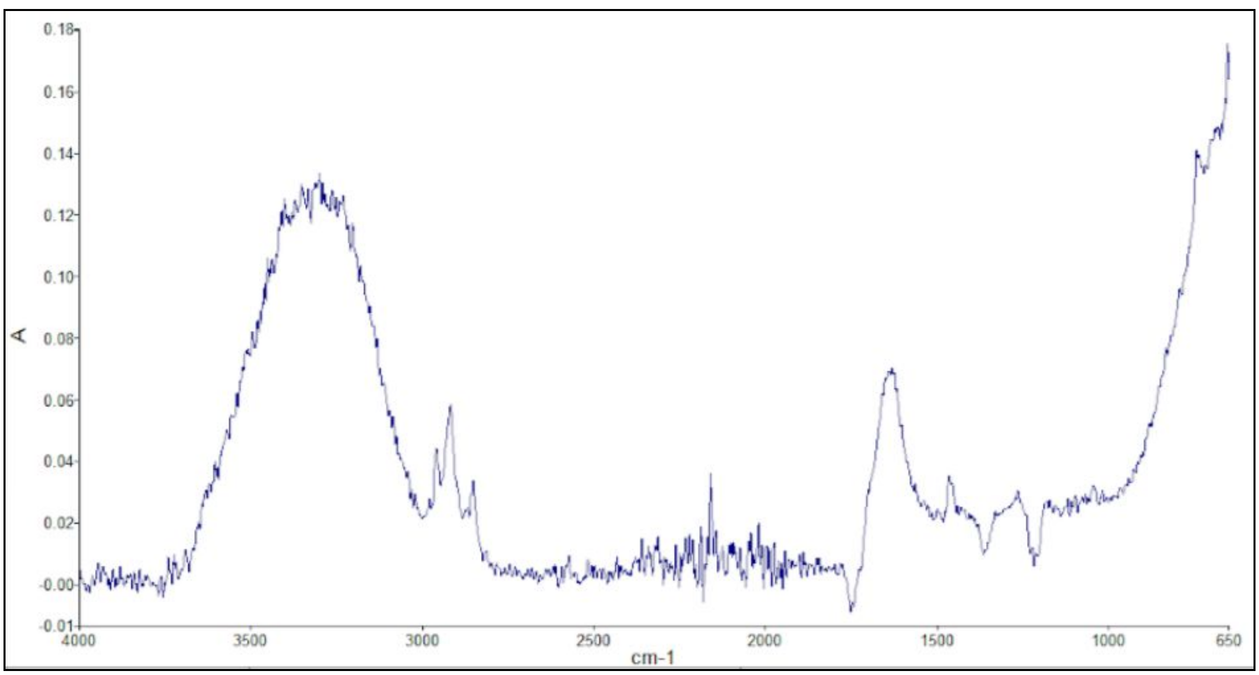

Figure 8: *Trial 1 IR Spectroscopy Graph for Bud Light hopped with Vic Secret*

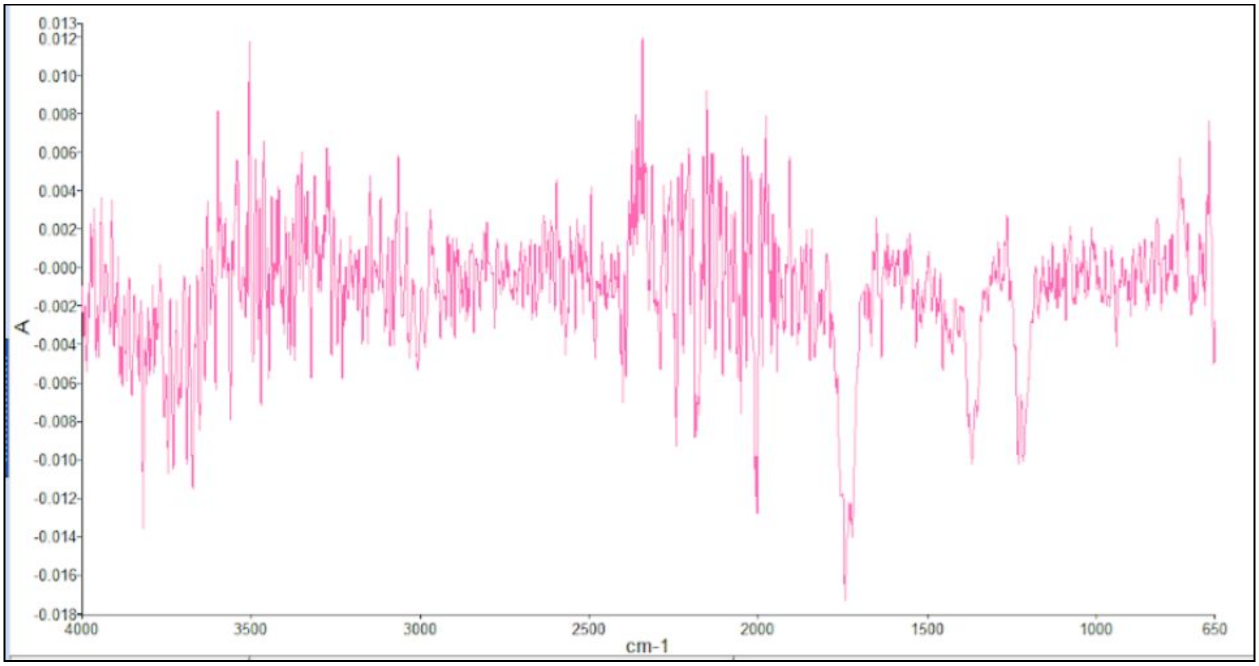

Figure 9: *Trial 2 IR Spectroscopy Graph for Bud Light hopped with Vic Secret*

Because of the inconsistency in the resulted graphs, we made the decision to discontinue using IR spec for the remainder of the project.

4.3 Analysis of Specific Gravity and pH

To further find any trends or correlations, we decided to do additional tests on the characteristics of the beer we created. The major areas we focused on were specific gravity and pH. With these areas greatly influencing alcohol percentage and acidity respectively, we tried to find correlations between these characteristics and the flavor score given. To maximize our time in the lab we ran these tests only on the beer we made with Purgatory Brewery's wort. Our full set of raw data can be found in Appendix E.

4.3.1 Trends of Specific Gravity on Flavor

To find if there were any correlations between specific gravity on flavor, we graphed the flavor score of each beer combination versus its respective specific gravity. Due to the differences we observed between double and triple combination as well as variance in scoring at seperate taste panel times, we have separated the data for each combination test. Our resulting graph is shown below:

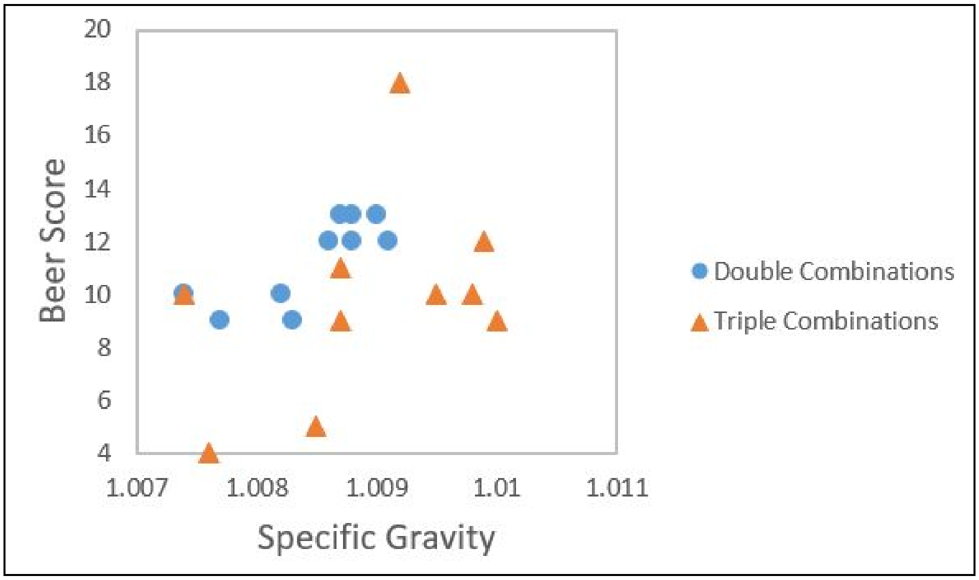

Figure 10: *Graph of the various beer scores associated with the measured specific gravity*

As can be seen above, a clear and definite correlation cannot be made. It can be observed that, generally, the beer scores trend upward as specific gravity increases. Optimally, this graph would show the relationship between alcohol percentage and beer score. Since we did not measure the specific gravity of the initial wort, we could not calculate the alcohol percentage. But, we can assume that at a lower specific gravity, there is more deviation from the initial specific gravity and therefore a higher alcohol percentage. Thus, this general trend makes sense since we got lower flavor scores at lower specific gravity. The alcohol percentage at these values is the greatest of our sample size so it makes sense that there might not be as much of a 'pleasant' taste to them.

4.3.2 Trends of pH on Flavor

We decided to also look at pH as it is a great indicator of acidity. The trials tested at separate panel tasting were again separated to isolate our two variables of interest as much as possible. Our resulting graph is shown below:

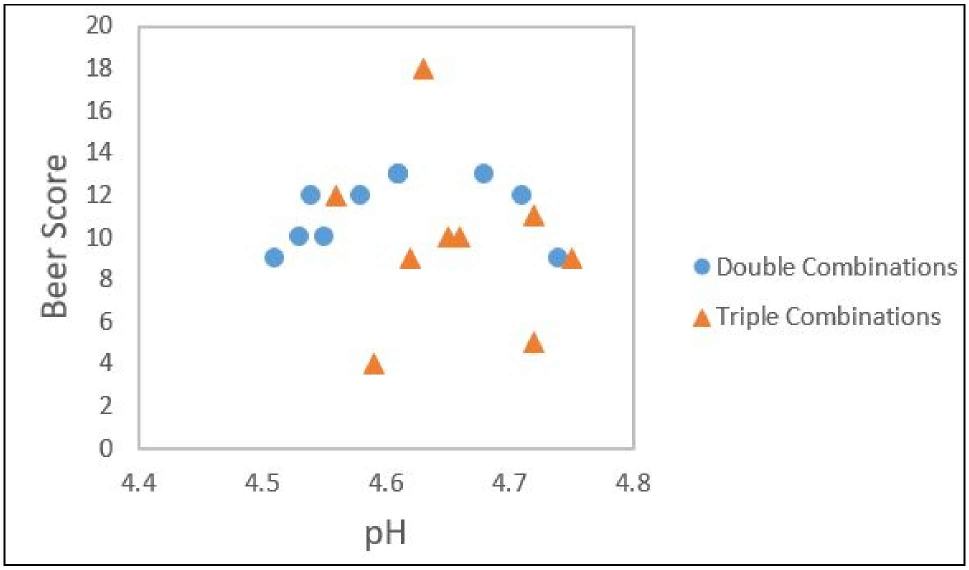

Figure 11: *Graph of the various beer scores associated with the measured pH.*

As can be seen above, there is not much of a trend that can be seen in both trials. pH measures the acidity which corresponds to the citrus flavor of the beer. This can be a more personal preference in terms of flavor which can explain the fact that no trend can easily be applied. It is important to note that in both trials, the high scores occurred in the center of the samples around a pH of 4.63. This further supports our theory that pH is probably more of a personal preference as neither extreme had high scores. The data point at a pH of 4.56 for the triple combinations did have a relatively high beer score, but we theorize that if the samples had more data points at the lower pH's, their scores would be lower. The data for the triple combinations is much more 'scattered' making it hard to predict trends.

4.4 Viability of a Hop Flavor Map

Initially, our final goal was to create an overall map documenting the outcoming flavors of various combinations of hops. This would be especially useful to brewers as they could predict or get a general idea of the resulting flavor of a new combination of hops. It would also be useful for brewers targeting a specific flavor or taste to pick their hops. For us, we would have liked to explore the correlations between compounds and the resulting flavors as well as the strengths at which hops accentuate each other.

From analysis of our data, we were unable to come up with an overarching flavor map. There was simply too much uncertainty in our data and inability to create strong correlations. As a result, we could not definitively come up with predictions for different hop combinations. We did not want to force fits where the correlations were not backed up in numerous trials and so did not find as many predictors as we had hoped. Therefore, we were unable to create this map, but for future tests, we would suggest on an increased number of trials to find create strong correlations. We would also suggest a wider variety of trials containing different hops to fully develop the effects of hops on each other. Finally, another source a future test could focus on is the variance of concentration to truly understand the effect of strength of each hop on each other.

4.5 Sources of Error

In regards to the final experiment that was conducted, there were several sources of error that may have influenced our results. The first source of error present was that taste tests were performed on four different days (Bud Light combinations of two on one day, Bud Light combinations of three on a different day and similarly with the hopped beer with Purgatory's wort). This inconsistency made it not possible to compare the tests from one day to the other due to subjectivity of the panel. Multiple times throughout the experiment, the panel member compared his opinion on the beer to the previously tasted beers, where the first beer tested that day was the baseline. The ranges that were seen from day 1 of testing compared to day 2 and so on were very different and again made difficulties for comparing the different days. Additionally, on the last day of testing the panel member gave one of the beers a score of 18 for flavor and stated that he did this to make one sample a "winner." Once again, because the beers were tested on different days, this score of 18 was much higher than any other scores given throughout the testing with the next highest score being a 14, but based off his comments from the beers, it seemed as though he preferred the beer with a score of 14. Because of these differences, we were not able to compare the experiments performed on different days.

A second source of error that was present throughout our experiment was that there was only one person on the tasting panel. This project was based off the preference of the owner of Purgatory Beer Co. (Brian), but to determine customers opinion on the different beers, it would be beneficial to have a larger panel. If there was more people on the tasting panel, there could be less of a difference from different days of testing. Additionally, the testings were performed at different times throughout the day and the tester had different physical and emotional moods on these days. Having a larger panel could help limit this subjectivity.

The two previous sources of error were primarily due to human error, but there were also errors associated with the experimental setup that may have influenced the testing. Because we had to account for our group's availability in addition to Brian's availability, the timeline in which beer was hopped to when it was tested different throughout the four different tests. Our group tried to keep the timeline for this to 5-7 days. Additionally, the timeline for how long the beer sat prior to being prepared and tested in the GC-MS differed from trial to trial. To reduce the deviation for the taste testing and GC-MS results, a set hopping, taste testing, and GC-MS sample preparation and testing should be strictly followed.

A second experimental error that was very prevalent in our experiment was associated with the two trials containing Brian's wort. Although Brian gave our group 5 L of Purgatory's Two Car DIPA for both our trials using his wort from the same fermentor, the 5 L was taken on two different days, at different stages of the fermenting process. Because of this, there were different levels of yeast in the sample taken at an earlier date than the sample taken on a later date. On the final day of testing, Brian mentioned multiple times that he believed the flavor was being influenced by the yeast present in the samples. He believed the prickly and dirty taste that was experienced in many of the trials on the final day of testing was due to the fermenting yeast. The second trial with Purgatory's wort had more settled yeast than the first trial and therefore the taste associated from the yeast had a larger presence in the tasting. To limit this, it would be beneficial to take a 10 L sample from Purgatory's wort and then filtering out the yeast prior to the taste test.

5. Conclusions and Recommendations

The purpose of our project was to analyze the chemistry of different hops combinations and concentrations in beer, with the goal of finding flavor correlations between hop combinations. Our results were largely qualitative as they were based on the preferences of the beer tasting panel. Due to this, we were able to find some general correlations between good and bad beer. GC-MS analysis proved very helpful for this purpose; using our GC-MS data, we were able to see exactly what compounds were in different combinations and concentrations of hops by narrowing down the characteristic compounds from the peaks 2, 3, and 4 from the GC-MS data. While we initially believed IR Spectroscopy to be a useful analytical tool for our purposes, we did not find our IR Spectroscopy data to be useful in identifying compounds in a variety of hops combinations. A key result we found was that the concentration of hops greatly affected the final score making it hard to predict with certainty the quality of the final beer. For example, citra-citra was the top combination in single hop trials, but was third in double hop trials and fourth in triples. We were interested in exploring methods to determine the different compounds in beer and we believe we have set the foundation for future trials and tests.

For future tests, we believe several factors from our project can be modified to create more accurate results. The main factor was the taste panel - more testers on a taste testing panel will provide a greater variety of perspectives, eliminating outliers and providing a wider perspective on what is “good” beer and what is “bad”. A noteworthy error within our experimentation was the fact that different testing days resulted in vastly different taste test scores. For our results, we suggested that each test should be treated separately and not used to compare against each other. However, if all of the tastes tests could be performed in one day, this would eliminate the variability that we saw between each day of tests. Furthermore, we suggest each taste test is random and anonymous as to get a completely unbiased score. Finally, we suggest that the same base be used for all trials. From our results, we noticed significant deviations from our Bud Light trials to the trials with Purgatory’s wort. Therefore, we conclude that dry hopping with Bud Light saves monetary value for the brewery and is a good basis for testing the procedure, but is not viable in the real tests. We believe our scoring card was a good representation of the beer and if the testing conditions could be standardized, a better picture could be viewed.

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Appendix A: Beer Scorecard

Beer Sample Number: _____ **Taste Tester Name: ________________________**

Aroma

Range

Unpleasant											Great
1	2	3	4	5	6	7	8	9	10	11	12

Descriptions that apply:

Notes:

Appearance

Range

Appealing		Unappealing
1	2	3

Descriptions that apply:

Notes:

Flavor

Range																			
Disgusting																			Delicious
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20

Descriptions that apply:

Notes:

Mouthfeel

Range				
Pleasant				Unpleasant
1	2	3	4	5

Descriptions that apply:

Notes:

Overall Impression

Range

Do not prefer this beer									Prefer this beer
1	2	3	4	5	6	7	8	9	10

Notes:

Descriptions by Category

Aroma

Basic Notes in Beer: malty, grainy, sweet, corn-like, hay, straw, graham cracker, bicuity, caramel, toast, roast, coffee, espresso, burnt, alcohol, tobacco, gunpowder, leather, pine, fresh cut grass

Dark Fruit Aromas: raisins, currant, plum, dates, prunes, figs, blackberry, blueberry

Light Fruit: banana, pineapple, apricot, pear, apple, nectarine, peach, mango, prickly pear

Citrus Notes: lemon, lime, orange, tangerine, clementine, grapefruit, Curaçao orange peel, lemon zest

Other Acidic-Type Aromas: metallic, vinegar, copper, cidery, champagne-like, astringent, chlorine

Spices, Yeast, etc: phenolic, white pepper, clove, anise, licorice, smoked bacon, fatty, nutty, butterscotch, vanilla, earthy, woody, horsey, fresh bread, saddle, musty, barnyard

Appearance

Beer Color: honey, caramel, russet red, brown, root beer, amber, chestnut, dark red, apricot, orange, black, burnt auburn, garnet, ruby, copper, deep gold

Beer Clarity: brilliant, hazy, cloudy, turbid, opaque, clear, crystal, bright, dull

The Beer's Head: persistent, rocky, large, fluffy, dissipating, lingering, white, off white, tan, frothy, delicate. To help with the beer's head retention, try adding flaked wheat (at NorthernBrewer.com) or add flaked barley.

Flavor Notes

Beer Notes: roasted, bready, bitter, sweet, spicy, fruity, chocolate, caramel, toffee, coffee, malty, tart, subtle, woodsy, earthy, sulfuric

Intensity: assertive, mild, bold, balanced, robust, intense, metallic, harsh, complex, delicate, refined, hearty

How Beer Taste Evolves: rolls into…, evolves into…, dissipates to reveal…, displays..., underlying…, suggests hints of…, fades to...

The Beer's Finish: dry, fruity, sweet, alcoholic, warming, bitter, acidic, buttery, wet, quenching, lingering

Mouthfeel

A Beer's Mouthfeel: smooth, silky, velvety, prickly, tingly, creamy, warming, viscous, hot, astringent, oily

Beer's Carbonation Level: spritzy, champagne-like, prickly, round, creamy, light, gassy, sharp, delicate

The Beer's Body: full, heavy, dense, viscous, robust, medium, balanced, medium-light, light, delicate, wispy

Appendix B: Taste Testing Panel Results

Bud Light Combos of Two

Hop Combo	Aroma	Aroma descriptions /notes	Appearance	Appearance descriptions /notes	Flavor	Flavor description/notes	Mouthfeel	Mouthfeel descriptions/notes	Overall Impression	Other notes:
G/G	6		1	1.5	6	mild, not bitter, malty, subtle, tart	4	smooth, light, light body	5	
Ce/G	4		2	lighter than G-G	5	little bit bitter, malty, mild intensity,	3	malty, tingly, creamy, spritzy, prickly for carbonation, viscous for beers body, light	4	does not evolve when you drink it
VS/G	7	likes It because its different, hay, straw, caramel, not fruity, little bit of lemon, little pine,	2	2.5, floaties of hops, darker than first two	6	malty, caramel, earthy, mild intensity, don't evolve through drinking it, pine	3	prickly, creamy, light, grassy carbonation level	5	5.5
M/M	7	sweater than bud light, pear,	1	super light, amber, least appealing because its so light, rain water, looks little dirty	8	tastes better than the rest, fruity, yet subtle,	4.5	4.5, silky, light for carbonation, body is medium light	6	best one so far
Vs/Ce	5	smells like cream ale, corn like, cut grass, malty from bud light	2	darker, little bit orange, little hazy, honey color	4	stays in your mouth, malty, earthy	1	not pleasant, tingly, creamy for carbonation, medium	2	not impressed

Vs/Vs	2	diaper, smells the worst, doesn't have a strong smell,	3	like this one the best so far, clearer	2	little bit of banana, sour, this ones bad	2	prickly, viscous, creamy, light	2	don't like, closest to disgusting
M/Ce	6	bitter from centennial, pretty good, sweet from mosaic, nectarine, mango	2	very nice, hazier than the last one, 2nd nicest, 2.75	7	good, sweet, fruit, mild intensity, smooth, starts sweet and goes to bitter at the end	4	smooth, silky	7	good good
Ce/Ce	2	not much going on with this one, almost no aroma, little bit of apricot	2	things floatin, darker, 2.5, clearer	1	very bitter, bad after taste, sulfur, malty	1	bad, prickly,	1	disgusting
M/G	8	very fruity, smells awesome, sweet, orange, grapefruit, citrus,	3	nice color, hazy,	9	fruity, citrus, bitter on back end,	3	smooth	8	good one, right up at the top
Ci/Ce	8	pear, fruity,	3	very hazy, light, third favorite	8	good, sweet, no aftertaste, subtle, stays smooth	4	great, 4.5 pleasant	8	like this one
M/Vs	3	burnt toast, dark fruit, prunes, second worst,	1	darker color, chalky looking, blah, 1.5, cloudy	1	very strong, after taste, very bitter, stays in your mouth, earthyl, harsh, worst flavor	1	bad, prickly, sharp, harsh, gaggy	1	disgusting
Ci/Ci	8	smells great, grapefruit,	3	very cloudy, hazy, nice, third	9	good, likes it, sweet, fruity, subtle,	4	smooth	9	best taste yet

		tangerine, citrus 8.5, best one yet		favorite		mild not intense, not bitter at the end, extra fruit at end, 9.5, best one yet				
Ci/G	5	sweet, malty, little bit of pear, above average	1	below average, not great, 1.5, cloudy	3	very mild, subtle, bland	2	fine, smooth, nothing going on	2	eh, watery, bland, 2.5
Ci/M	7	sweet, nice, peach, light fruit, apricot, pear, one of the higher ones	1	light color, not great, cloudy, chalky	4	good, very smooth, not as great as it smells, mild, subtle, bready, no fruit	2	very smooth, no after taste, light	4	let down, unimpr essed
Ci/Vs	4	smells earthy, piney, wet cellar, juniper, don't like it	1	too light, chalky, murky, no orange, pale yellow	1	malty, piney, bitter, earthy, woodsy, second worst	3	tingly and pricky, same carbonatio n	2	on the low end,

Bud Light Combos of Three

Hop Combo	Aroma	Aroma descriptions/notes	Appearance	Appearance descriptions /notes	Flavor	Flavor descriptions/notes	Mouthfeel	Mouthfeel descriptions/notes	Overall Impression	Other notes
M-Ce-Ci	6	(start in the middle 6/6.5) good and bad, pineapple, earthy	2	chalky, pale yellow, carbonation same for all of them	6	fruity, but also harsh, sweet,	2		5	
M-G-Ci	7	mild, citrus, lemon, skunky smell	3	nicer than first one, nice and cloudy, orangey color too,	13	sour but fruity, balanced, a little bit tart,	3	good, smooth, a little tingly, spritzy (sour)	7	
G-Ci-VS	2	skunky smell, earthy, bread, copper, not good, not getting pine,	3	nice appearance, little darker than last, very similar to that one	2	Super bitter, intense, harsh, little of caramel, not good	1	gross, bad aftertaste, viscous, prickly, sharp, dense	2	
M-G-VS	3	getting a little bit of citrus, piney, a little bit of apricot, orange	1	very watery, clearer than first, pale, translucent,	1	real bad aftertaste, dirty on back end, ginger	1	real bad, worse one	1	
M-Ci-VS	4	mild, smell the pine, corn, grainy,	2	not as pale as the first one, amber, caramel, not hazey, cloud	2	bitter, bready, intense, not good, somehow gets	1	chalky, not smooth, prickly,	1	1.5 for overall impression

						worse,				
G-Ce-Ci	6	a little bit of straw, little bit of orange, a little smokey	2	honey, somewhat clear	14	pretty good, smooth, turns thin on the back end	4	smooth, silky, light	8	
M-Ce-VS	4	piney, sour, hay and straw,	2	little bit of an orangey, yellowish orange, cloudy	2	real bad, bitter, bready, piney, intense	1	prickly, hot	1	
Ce-Ci-VS	6	Citrusy, fruity, marshm allow,	3	nice, hazy dark yellow	7	First drink is smooth, sweet, dissipate s to reveal bitter and chalky	2	Bad, prickly, started smooth and ended prickly and chalky	2	
G-Ce-VS	2	smells a little fishy, seahors e	2	chalky, cloudy, pale	11	pretty smooth, hart, woodys, subtle,	4	smooth	6	
M/G/C e	8	smells really good, orangey, citrusy,	3	Pale orangey, nice.	15	Great, sweet, fruity, smooth, consiste nt	4	smooth, balanced, nice	9	
4x Ci	8	smells like bubbleg um, orange peel, citrus tangerin e,	3	pretty orange	12	sweet in front, bitter on back end didn't like it (from seeping hops), little bit fruity	2	smooth unfront, then hoppy, 2.5	7	

						tart, mild, refined				
2x Ci	8	smells just like 4x citra	2	less orangey the 4x citra, opaque, 2.5	9	lot more bitter than 4x, not as good as 4x citra, fruity, back end had got thin and peanut, end is not good	2	viscous and then thin, not good	5	
2x M	7	lemony, little bit of pear, not as strong as 2x and 4x citra	3	opaque, good amber color, hazy, more yellow than orange	10	lemony, citrus, pinapple, doesn't change at the end, same flavor througho ut	4	nice and smooth, no bitter at the end	6	
4x M	6	doesn't really smell like anything , little bit of orange and apricot, very slight	2	light orange color, 2.5	9	sweet, not bitter, fruity, gets watery at the end a little bit, thins out	4	nice, a little pricky/ tingly	6	unim press ed

Purgatory Wort Combos of Two

Hop Combo	Aroma	Aroma descriptions /notes	Appearance	Appearance descriptions /notes	Flavor	Flavor descriptions/notes	Mouthfeel	Mouthfeel descriptions/notes	Overall Impression	Other notes
G/G	6		1	1.5	6	mild, not bitter, malty, subtle, tart	4	smooth, light, light body	5	
Ce/G	4		2	lighter than G-G	5	little bit bitter, malty, mild intensity,	3	malty, tingly, creamy, spritzy, prickly for carbonation, viscous for beers body, light	4	does not evolve when you drink it
VS/G	7	likes It because its different, hay, straw, caramel, not fruity, little bit of lemon, little pine,	2	2.5, floaties of hops, darker than first two	6	malty, caramel, earthy, mild intensity, don't evolve through drinking it, pine	3	prickly, creamy, light, grassy carbonation level	5	5.5
M/M	7	sweater than bud light, pear,	1	super light, amber, least appealing because its so light, rain water, looks little dirty	8	tastes better than the rest, fruity, yet subtle,	4.5	4.5, silky, light for carbonation, body is medium light	6	best one so far
Vs/Ce	5	smells like cream ale, corn like, cut grass, malty from bud light	2	darker, little bit orange, little hazy, close to the beginning ones, honey	4	stays in your mouth, malty, earthy	1	not pleasant, tingly, creamy for carbonati	2	not impressed

				color				on, medium body		
Vs/Vs	2	diaper, smells the worst, doesn't have a strong smell,	3	like this one the best so far, clearer	2	little bit of banana, sour, this ones bad	2	prickly, viscous, creamy, light	2	don't like, close st to disgu sting
M/Ce	6	bitter from centennial, pretty good, sweet from mosaic, nectarine, mango	2	very nice, hazier than the last one, 2nd nicest, 2.75	7	good, sweet, fruit, mild intensity, smooth, starts sweet and goes to bitter at the end	4	smooth, silky	7	good good
Ce/Ce	2	not much going on with this one, almost no aroma, little bit of apricot	2	things floatin, darker, 2.5, clearer	1	very bitter, bad after taste, sulfur, malty	1	bad, prickly,	1	disgu sting
M/G	8	very fruity, smells awesome, sweet, orange, grapefruit, citrus,	3	nice color, hazy,	9	fruity, citrus, bitter on back end,	3	smooth	8	good one, right up at the top
Ci/Ce	8	pear, fruity,	3	very hazy, light, third favorite	8	good, sweet, no aftertaste, subtle, stays smooth	4	great, 4.5 pleasant	8	like this one
M/Vs	3	burnt toast, dark fruit, prunes, second worst,	1	darker color, chalky looking, blah, 1.5,	1	very strong, after taste, very bitter, stays in	1	bad, prickly, sharp, harsh, gaggy	1	disgu sting

				cloudy		your mouth, earthy as hell, harsh, worst flavor				
Ci/Ci	8	smells great, grapefruit, tangerine, citrus 8.5, best one yet	3	very cloudy, hazy, nice, third favorite	9	good, likes it, sweet, fruity, subtle, mild not intense, not bitter at the end, extra fruit at end, 9.5, best one yet	4	smooth	9	best taste yet
Ci/G	5	sweet, malty, little bit of pear, above average	1	below average, not great, 1.5, cloudy	3	very mild, subtle, bland	2	fine, smooth, nothing going on	2	eh, watery, bland, 2.5
Ci/M	7	sweet, nice, peach, light fruit, apricot, pear, one of the higher ones	1	light color, not great, cloudy, chalky	4	good, very smooth, not as great as it smells, mild, subtle, bready, no fruit	2	very smooth, no after taste, light	4	let down, unimpressed

Purgatory Wort Varying Combos of Three

Hop Combo	Aroma	Aroma descriptions/notes	Appearance	Appearance descriptions/notes	Flavor	Flavor descriptions/notes	Mouthfeel	Mouthfeel descriptions/notes	Overall Impression	Other notes
2 M, 2 G, Ce	9	pineapple, mango	2	orange, amber, nice	9	bad after taste, bitter at	2	prickly at the end, tingly, beginning	4	

						the end,		smooth		
G, Ce, Ci	7	very caramel, apricot,	2	darker amber, copper	10	caramel, sweet, little harsh finish because of yeast	2	smooth and the prickly because of yeast	5	
2 G, Ce, Ci	5	caramel and pear, not as strong as the one before, not very strong smell	2	almost the same as the previous one, copper, hazy	4	really bad, sweet, bitter, tart	2	no bueno, burning sensation, prickly, gross, heavy	2	
2 G, Ce, 2 Ci	7	not as caramel y, lemon/li me	2	more yellowish 2.5	10	starts sweet, smooth, bubblegu m, yeast on backend	3	one of the better ones	6	best one so far
G, Ce, 2 Ci	8	sweet, orangy, citrus, mango	2	nice, more yellow than the other ones, 2.5	11	lemony, mild, sweet	3		6	
M, G, Ci	9	caramel, sweet. banana	3	light orange, honey	18	sweet, fruity, balanced, smooth, banana	4	very smooth,	8	
M, G, Ce	4	very very light nectarin e and peach, not much of	2	light copper, pretty clear	12	roasted and sweet, caramel, not very citrus, mild,	3	3.5, not bitter at the end	7	

		an aroma								
2 M, G, Ce	4	not much of anything, hint of pear or peach	2	nice, caramel, honey color	9	very prickly, starts off smooth, turns bitter because of yeast	2	prickly at end	4	
M, 2 G, Ce	4	smells like a raisin	2		5	never changes, starts bad, ends bad, very bitter, skunks ass	1	gross, unpleasant, rusty naisl	2	

Appendix C: GC-MS Results

Bud Light Tests

Hop	Peak 1 abd	Peak 1 Cpd	Q	Peak 2 abd	Peak 2 Cpd	Q	Peak 3 abd	Peak 3 Cpd	Q	Peak 4 abd	Peak 4 Cpd	Q	Peak 5 abd	Peak 5 Cpd	Q	Peak 6 abd	Peak 6 Cpd	Q
M/G	112000	heptane 2,4 dimethyl	59%	123000	octane 6-ethly-2-methyl	59	121000	tridecane 6-methyl hexadecane nonane 3-methyl-5-propyl	72%	100000	eicosane pentacosane	86%	80000	2-bromo dodecane	86%	60000	pentaecane 3-methyl	53
G/Ci/Ce	160000	heptane 2,4 dimethyl	87%	210000	hexane 3,3 dimethyl 3-ethyl-3-methylheptane	59%	170000	decane, 2,3,6,-trimethyl	72%	150000	heneicosane	78%	130000	heptacosane	80%	100000	heneicosane	86%
M	zoom back in	heptane 2.4, dimethyl	95%		decane 4-ethyl	80%		pentadecane	72%		eicosane	90%		tridecane, 5-propyl	83%			
Ci/Ce	zoom back in	heptane 2.4, dimethyl	81%		sulfurous acid, butyl nonyl ester	59%		decane, 2,3,5-trimethyl	64%		octadecane, 1-iodo	86%		heneicosane hentriacontane	86%			
M/G/Ce	220000	heptane 2.4, dimethyl	58%	510000	decane 4-ethyl	80%	410000	heptadecane 8-methyl	90%	410000	pentadecane	78%	300000	eicosane hexadecane heneicosane	64%			

Ci	zoom back in	heptane 2,4-dimethyl	87%		decane, 4-ethyl	80%		dodecane, 4,6-dimethyl hexadecane decane, 2,3,6-trimethyl 3 ethyl-3 methylheptane	72%		heneicosane	72%		heptacosane	90%		heptacosane	87%
Ci/VS	110 000	heptane, 2,4, dimethyl	50%	150 000	undecane, 4,7-dimethyl	53%	120000	decane, 2,3,5 - trimethyl	64%	110000	eicosane	58%	100 000	2-bromo dodecane	58%			
Ce	zoom back in	heptane 2.4, dimethyl	76%		decane 4-ethyl	72%		tridecane, 1-iodo	78%		heptadecane,8-methyl eiocosane	90%		heneiocosane	80%			
M/Ce/VS	zoom back in	heptane 2.4, dimethyl	87%		sulfurous acid, heyl 2-pentyl ester sulfurous acid, decyl 2-propyl ester	50%		hexadecane 3-ethyl-3-methly heptane nonane,1-iodo tridecane, 6-methyl	64%		eicosane	91%		heptacosane	90%			
M/G/Vs	210 000	heptane 2,4-dimethly	90%	250 000	undecane 2,7dimethyl	64%	220000	hexadecane decane 2,3,5-trimethyl	72%	200000	tetracosane	83%	140 000	heptacosane	90%			
M/Vs	190 000	hexane 2-ethyl	53%	230 000	undecane, 5-methyl	59%	180000	Tridecane, 1-iodo	72%	140000	Docosane	80%	100 000	Heneicosane Eicosane	78%	90000	Heneicosane	86%
Vs	420 000	heptane 2,4-di	87%	550 000	decane 4-ethyl	72%	510000	dodecane 1-iodo	72%	380000	eicosane	80%	320 000	heneicosane	86%	240 000	heneicosane	90%

		methyl			decane 3,8-dimethyl			3-ethyl-3-methyl heptane			heneicosane							
G	zoom back in	heptane 2.4, dimethyl	87%		decane 4-ethyl	72%		tridecane, 1-iodo	78%		eicosane	90%						

Purgatory Wort Tests

Hop	Peak 1 abd	Peak 1 Cpd	Q	Peak 2 abd	Peak 2 Cpd	Q	Peak 3 abd	Peak 3 Cpd	Q	Peak 4 abd	Peak 4 Cpd	Q	Peak 5 abd	Peak 5 Cpd	Q	Peak 6 abd	Peak 6 Cpd	Q
Ci/Ce	330000	heptane 2,4-dimethyl	94%	340000	decane 4-ethyl	72%	380000	decane 2,3,6 trimethyl	80%	320000	heneicosane	80%	270000	heptacosane	90%			
2M/G	350000	heptane 2,4-dimethyl	91%	460000	sulufous acid, butyl nonyl ester	59%	400000	Octane, 5-ethyl-2-methyl- decane 2,3,6 trimethyl	80%	330000	heneicosane hexadecane	72%	260000	tetrapentacontane 1,5,4-dibromo-	83%			
M/M	270000	heptane 2,4 dimethyl	93%	360000	decane 3,7-dimethyl	87%	290000	hexadecane 3-ethyl-3-methylheptane eicosane	72%	230000	heneicosane	80%	160000	heneicosane	86%			
M/Ce	240000	heptane 2,4 dimethyl	83%	270000	sulfurous acid, butyl nonyl ester heptane 2,4-dimethyl	59%	230000	tridecane 1-iodo oxalic acid isohexyl nenopenyl ester	53%	160000	heneicosane	80%	110000	heneicosane	59%			

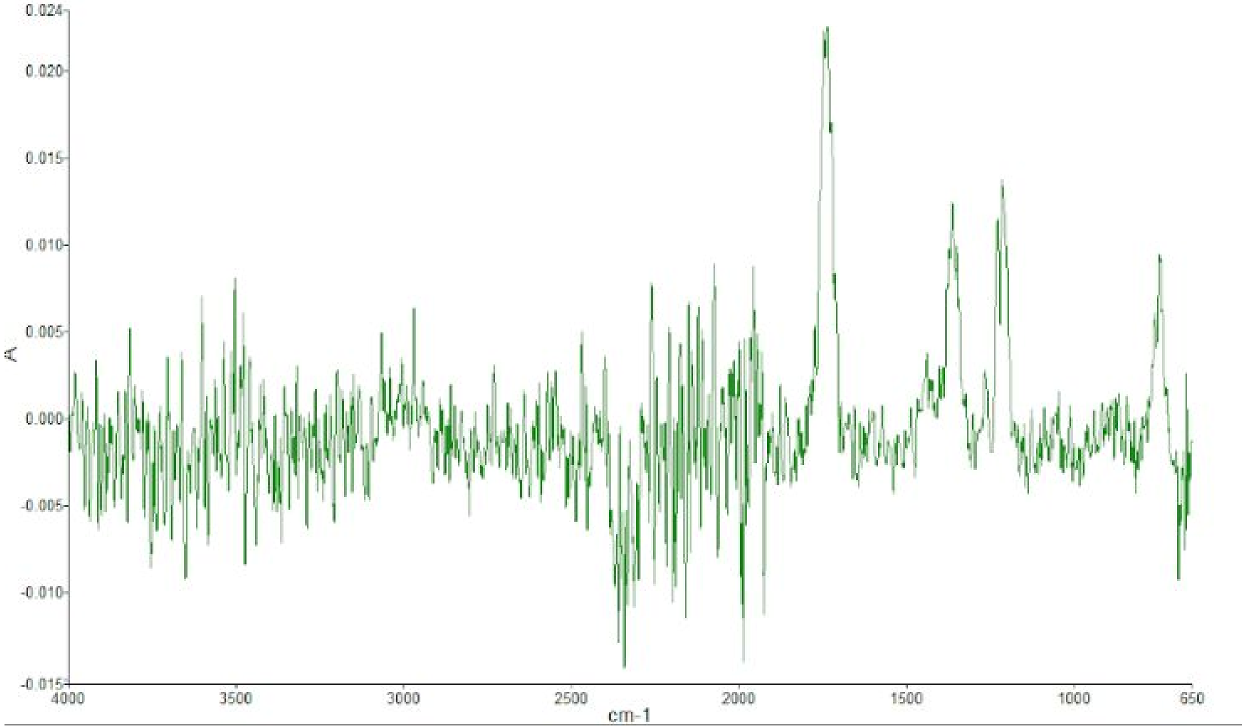
								sulfurous acid hexyl penyl ester										
											octadecane			pentadecane				
M/G	300 000	heptane 2,4-dimethyl	94%	360 000	hexane 3,3-dimethyl	59%	260000	3-ethyl-3-methylheptane	80%	180000	pentadecane	72%	120 000	2,6,10-trimethyl	86%			
								heptadecane 8-methyl			decane 2,3,6-trimethyl							
Ci/Ci	360 000	heptane 2,4-dimethyl	91%	370 000	hexane 3,3-dimethyl	59%	300000	hexadecane	83%	220000	tridecane, 1-iodo	72%	150 000	2-bromo dodecane	72%			
2M/2M	275 000	heptane 2,4-dimethyl	81%	330 000	decane 3,7-dimethyl	64%	290000		72%	200000	tetrapentacontane	78%	180 000	heptacosane	86%	130 000	henicosane	90%
					decane 5-ethyl-5 methyl						eicosane							
								pentadecane			octadecane							
											2-bromo dodecane							
2M/Ce	250 000	heptane 2,4-dimethyl	76%	300 000	decane 3,7-dimethyl	81%	270000	tridecane 1-iodo	59%	190000	tridecanol 2-ethyl, 2,1-methyl	78%	150 000	tridecane,1-iodo	83%	110 000	heneicosane	72%
	260 000	heptane, 2,4-dimethyl	87%	340 000	hexadecane	53%	240000		80%	190000		83%	110 000	tridecane, 1-iodo				
2Ci/Ce					hexane, 3,3-dimethyl			decane, 2,3,5-trimethyl			hexadecane			heptacosane				

					oxalic acid, isohexyl neopenytl ester									d, butyl				
								hexadecane			Heptacosane							
								Decane 2,3,6-trimethyl			Undecane 3-ethyl							
2M/G/Ce					Dodecane 5-methyl	64 %		Dodecane 4,6-dimethyl	72 %			72 %						
M/G/Ci					decane 4-ethyl	72 %		dodecane 4,6-dimethyl	72 %		heptacosane	80 %						
								decane 2,3,6 - trimethyl										
G/Ce/Ci					decane 4-ethyl	72 %		heptacosane	64 %		heneicosane	80 %						
M/2G/Ce					Decane 4-ethyl	80 %		dodecane 4,6-dimethyl	72 %		2-bromotetradecane	86 %						
2G/Ce/Ci					Decane 4-ethyl	80 %		Dodecane 4,6-dimethyl	72 %		2-bromotetradecane	86 %						

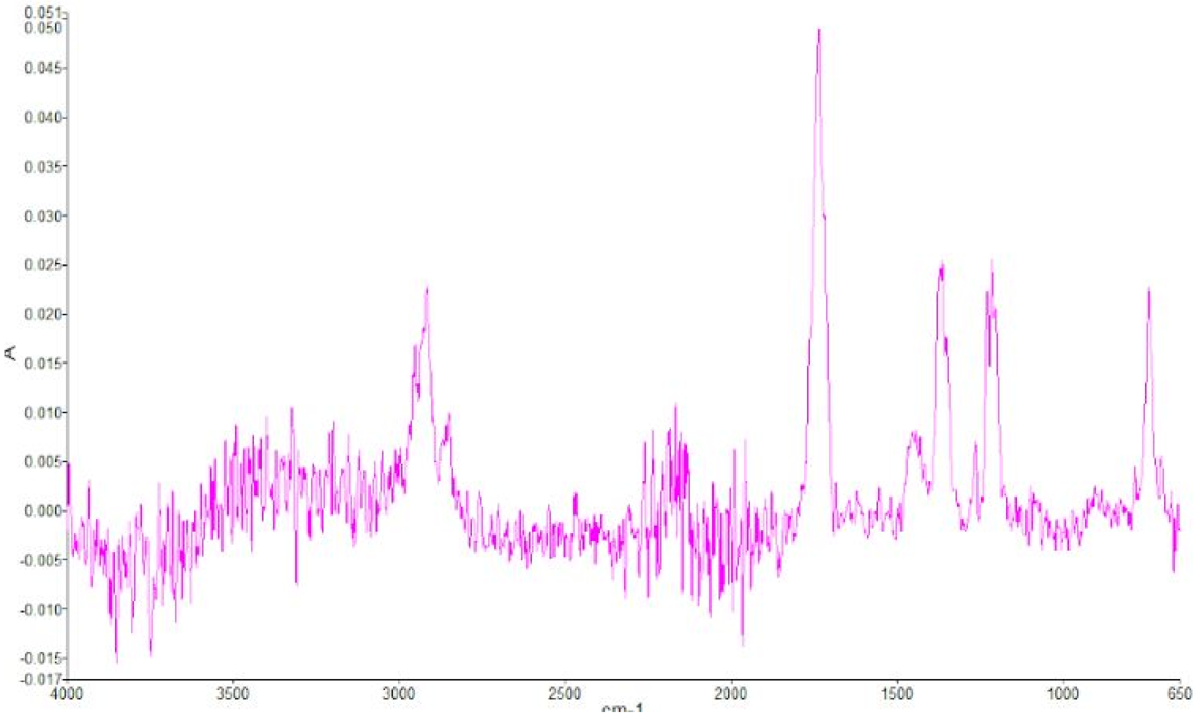
G/Ce/2Ci					Decane 4-ethyl	72 %		dodecane 2,6,11 trimethyl	74 %		octacosane	90 %						
											hentriacontane							
											heptacosane							
M/G/Ce					undecane 5-methyl	58 %		3-ethyl-3methyl heptane	72 %		heneicosane	90 %						
					sulfurous acid, hexyl pentyl ester	58 %												
2M/2G/Ce					Decane 4-ethly	72 %		Decane 2,3,6-trimethyl	80 %		Hexadecane	83 %						
2G/Ce/2Ci					Decane 4-ethyl	72 %		Hexadecane	90 %		Dodecane, 2-methyl-6-propyl	78 %						

Appendix D: IR Graphs

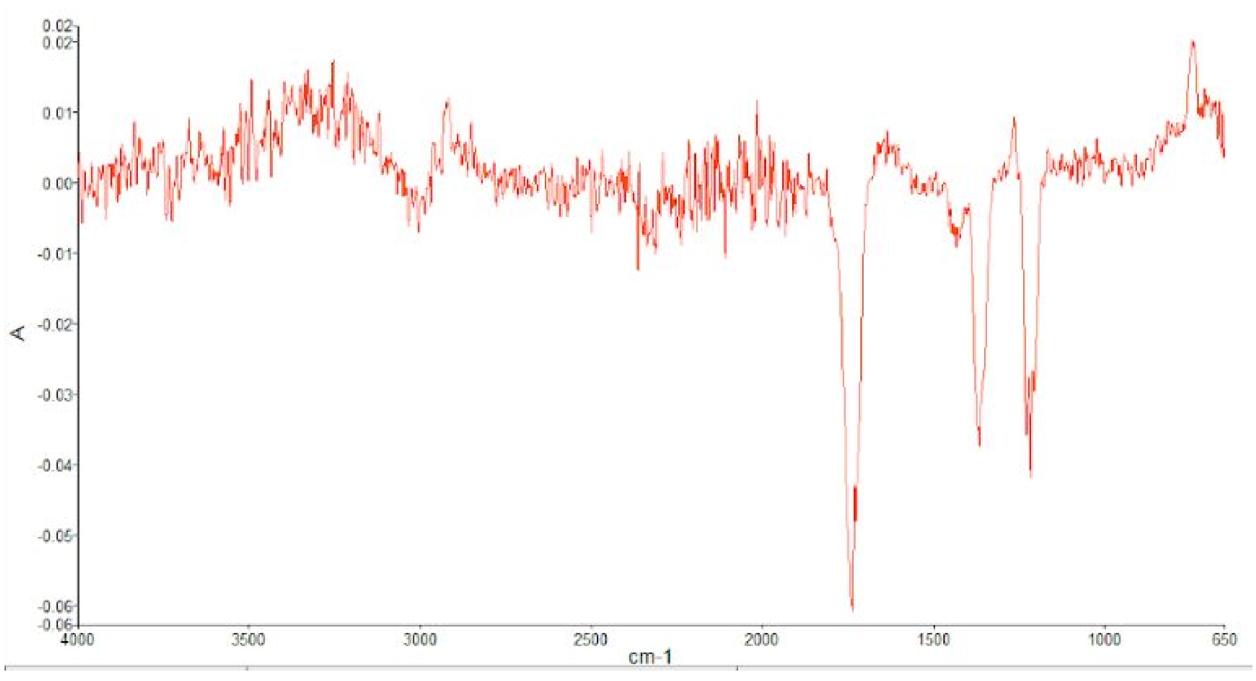
Centennial



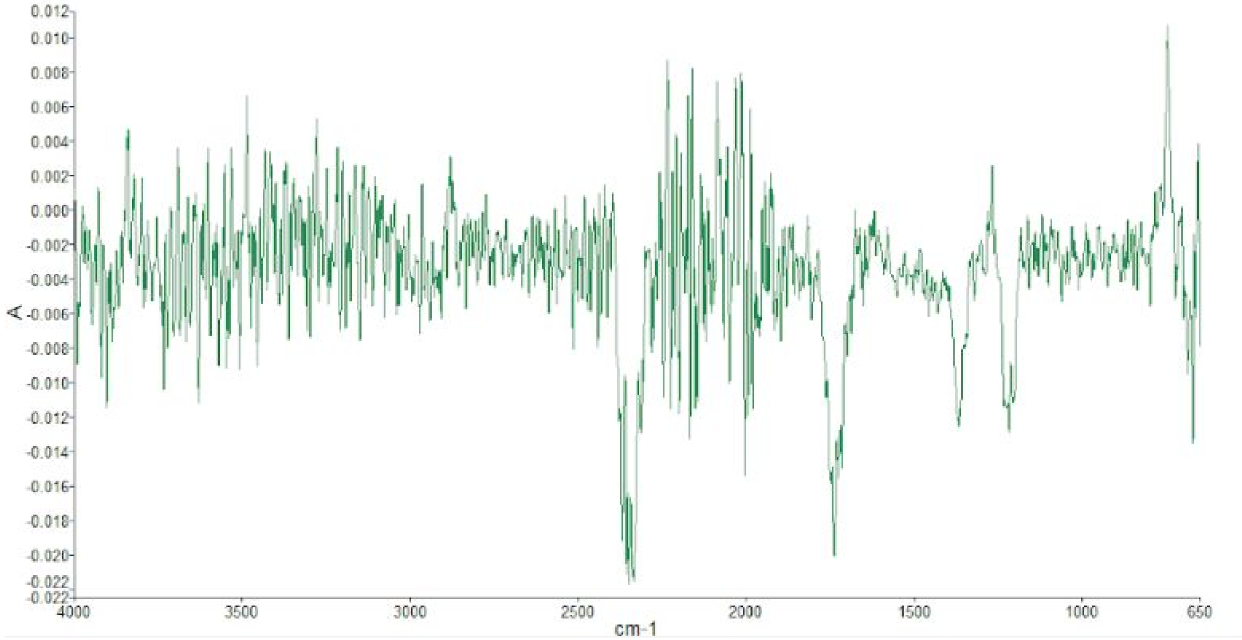
Citra



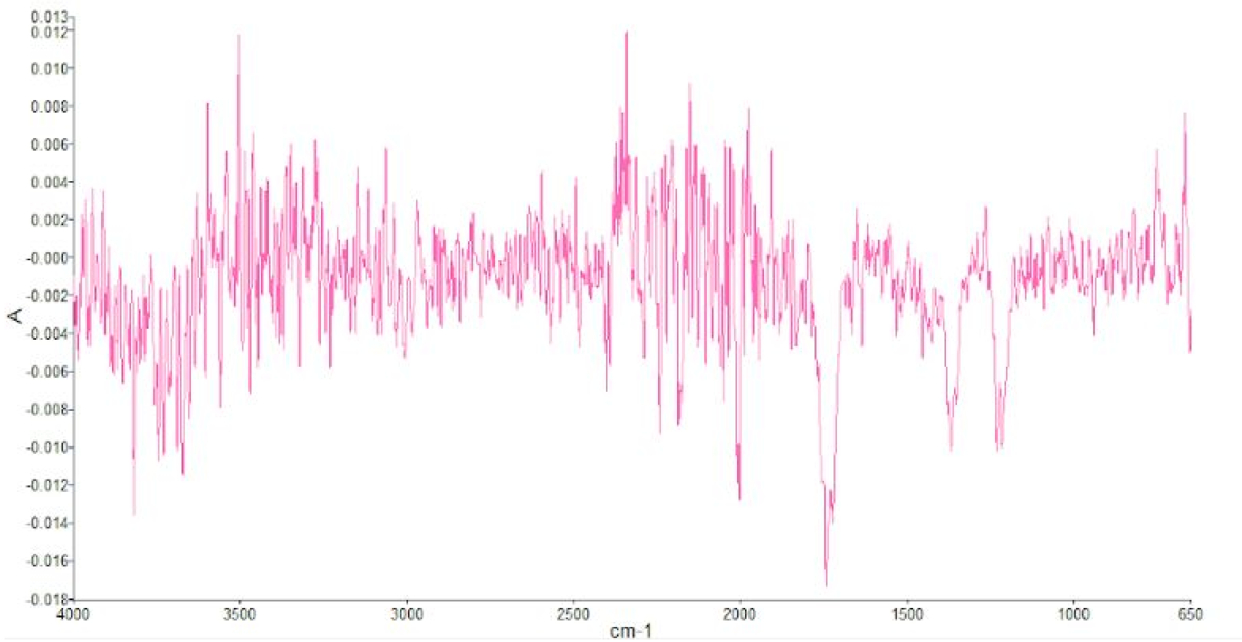
Galaxy



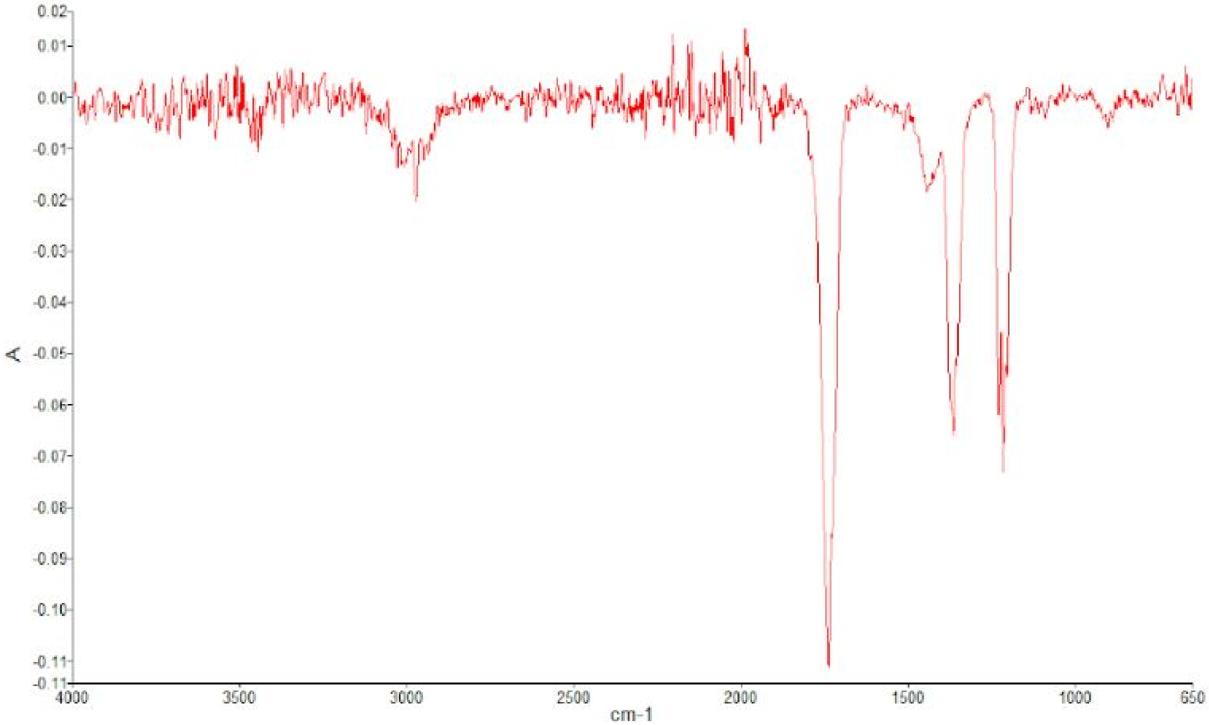
Mosaic



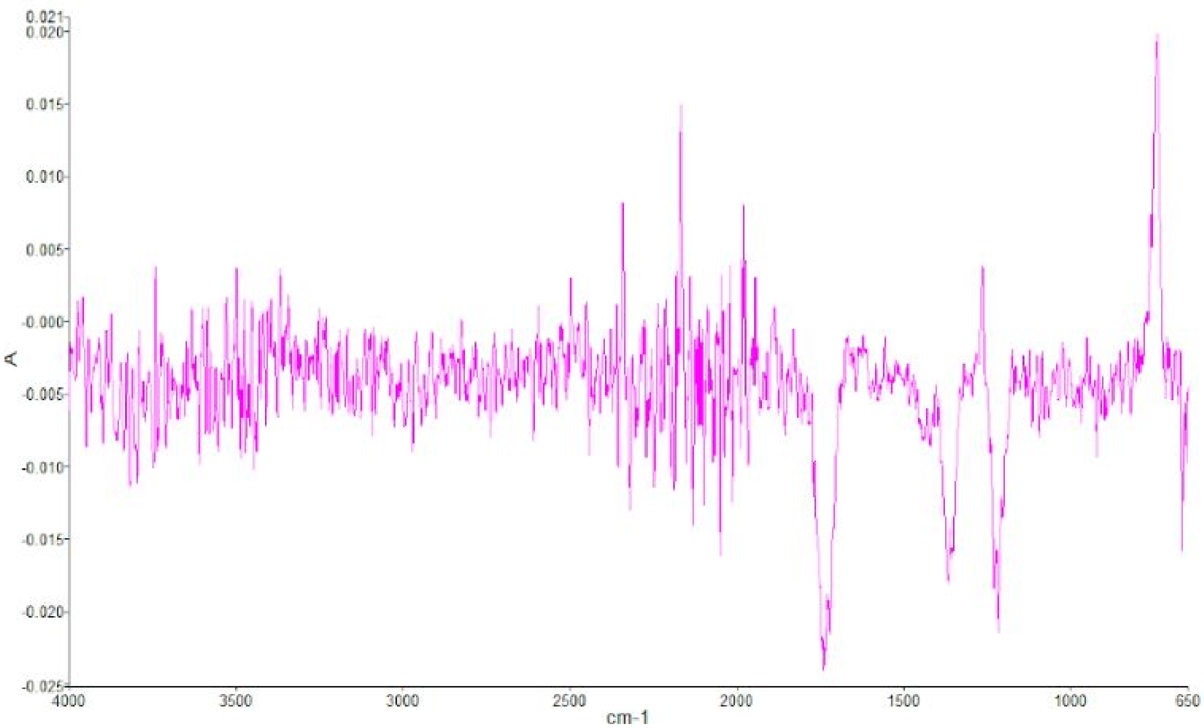
Vic Secret



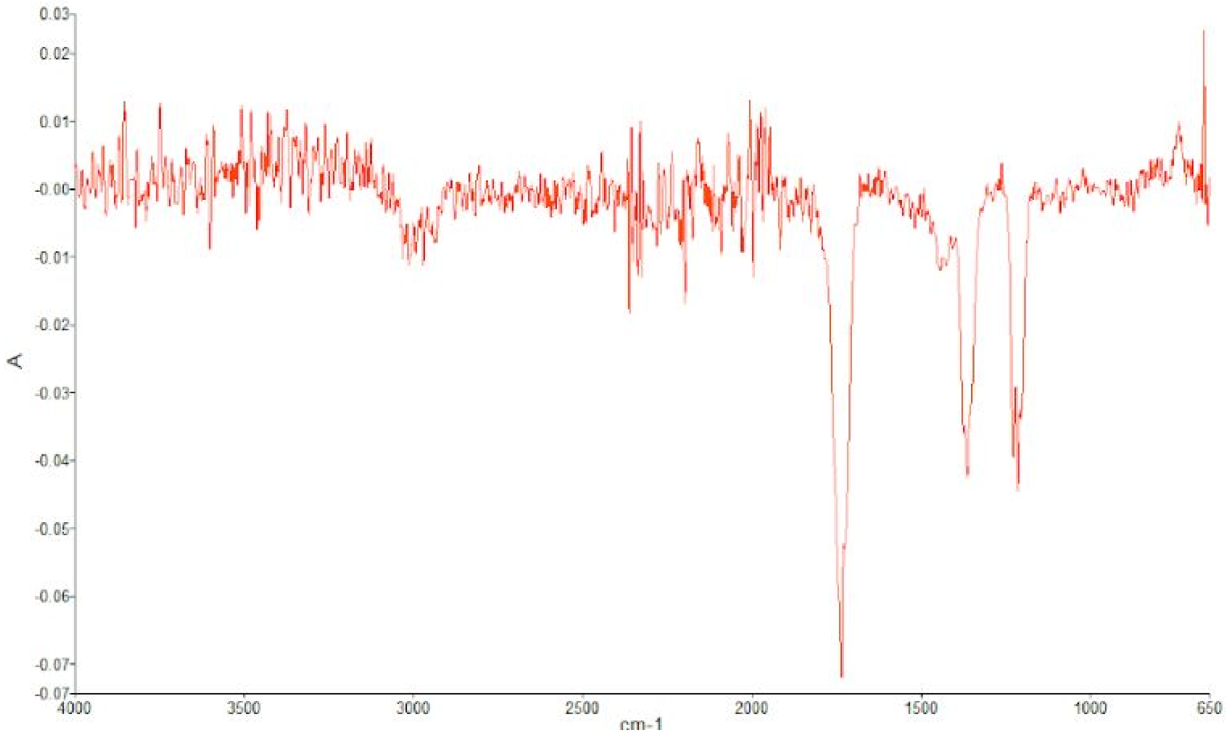
Ce/Ci


0.02
0.01
0.00
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
-0.07
-0.08
-0.09
-0.10
-0.11
-0.11
A
4000
3500
3000
2500
2000
1500
1000
650
cm-1

Ci/Vs


0.021
0.020
0.015
0.010
0.005
-0.000
-0.005
-0.010
-0.015
-0.020
-0.025
A
4000
3500
3000
2500
2000
1500
1000
650
cm-1

G/Ce/Ci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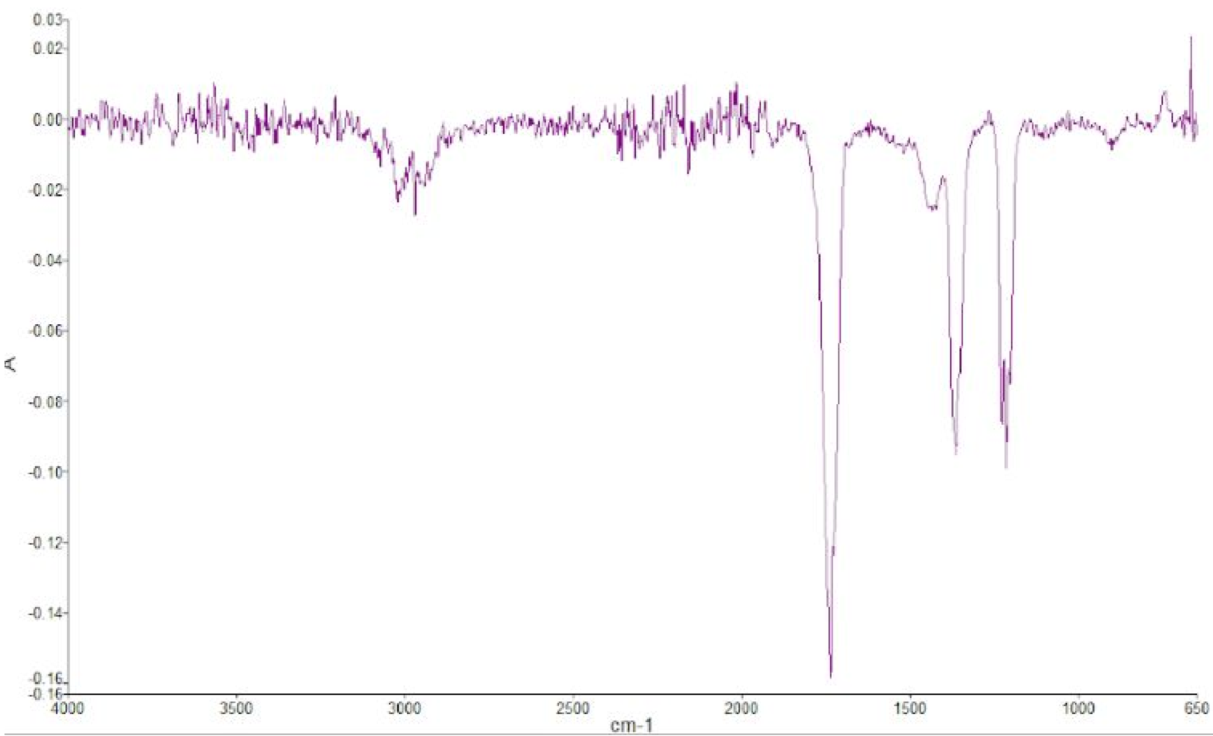
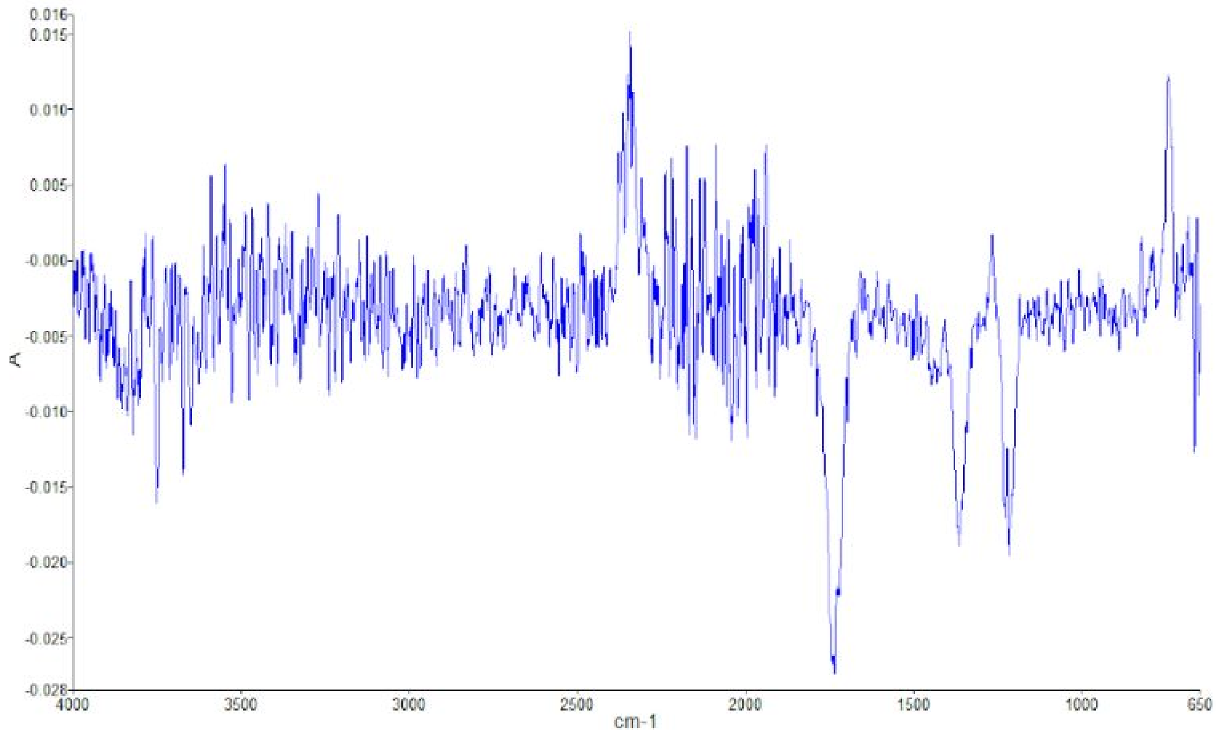
0.02
0.01
-0.00
-0.01
-0.02
A
-0.03
-0.04
-0.05
-0.06
-0.07
-0.07
4000
3500
3000
2500
2000
1500
1000
650
cm-1

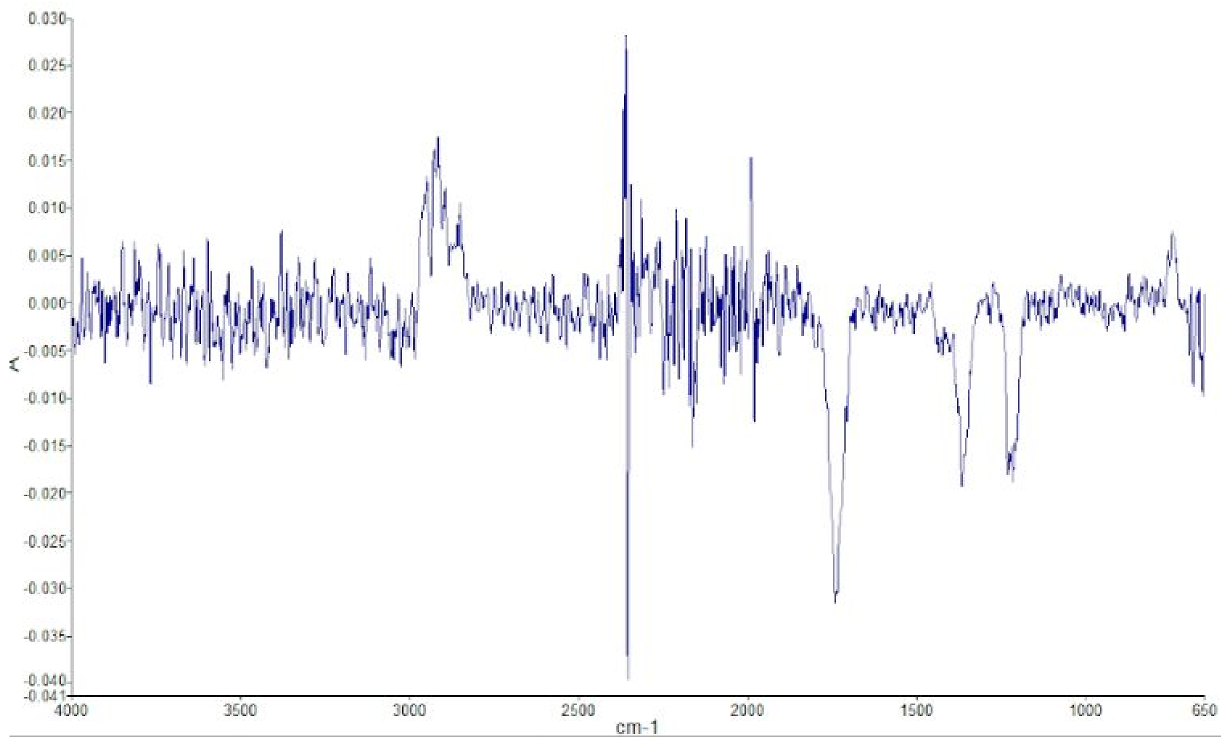
M/Ce/Vs


0.03
0.02
0.00
-0.02
-0.04
-0.06
A
-0.08
-0.10
-0.12
-0.14
-0.16
-0.16
4000
3500
3000
2500
2000
1500
1000
650
cm-1

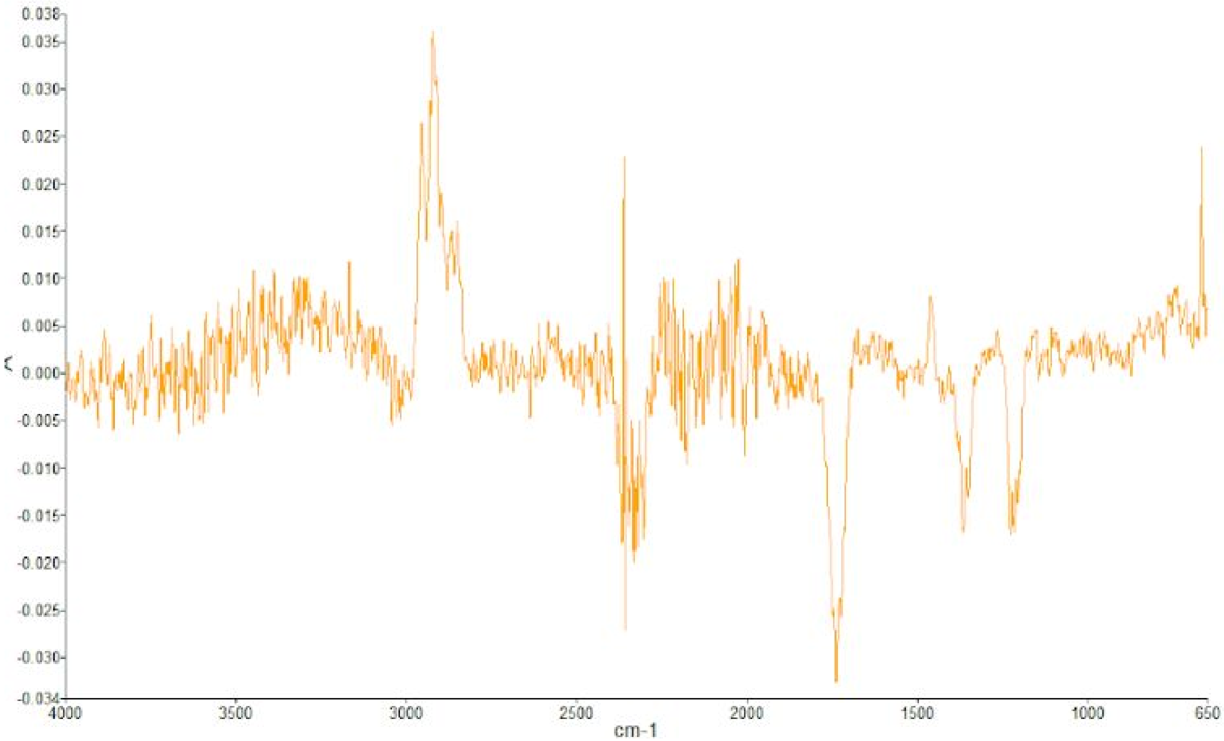
M/G


0.016
0.015
0.010
0.005
-0.000
-0.005
-0.010
-0.015
-0.020
-0.025
-0.028
A
4000
3500
3000
2500
2000
1500
1000
650
cm-1

M/G/Ce


0.030
0.025
0.020
0.015
0.010
0.005
0.000
-0.005
-0.010
-0.015
-0.020
-0.025
-0.030
-0.035
-0.040
-0.041
A
4000
3500
3000
2500
2000
1500
1000
650
cm-1

M/G/Vs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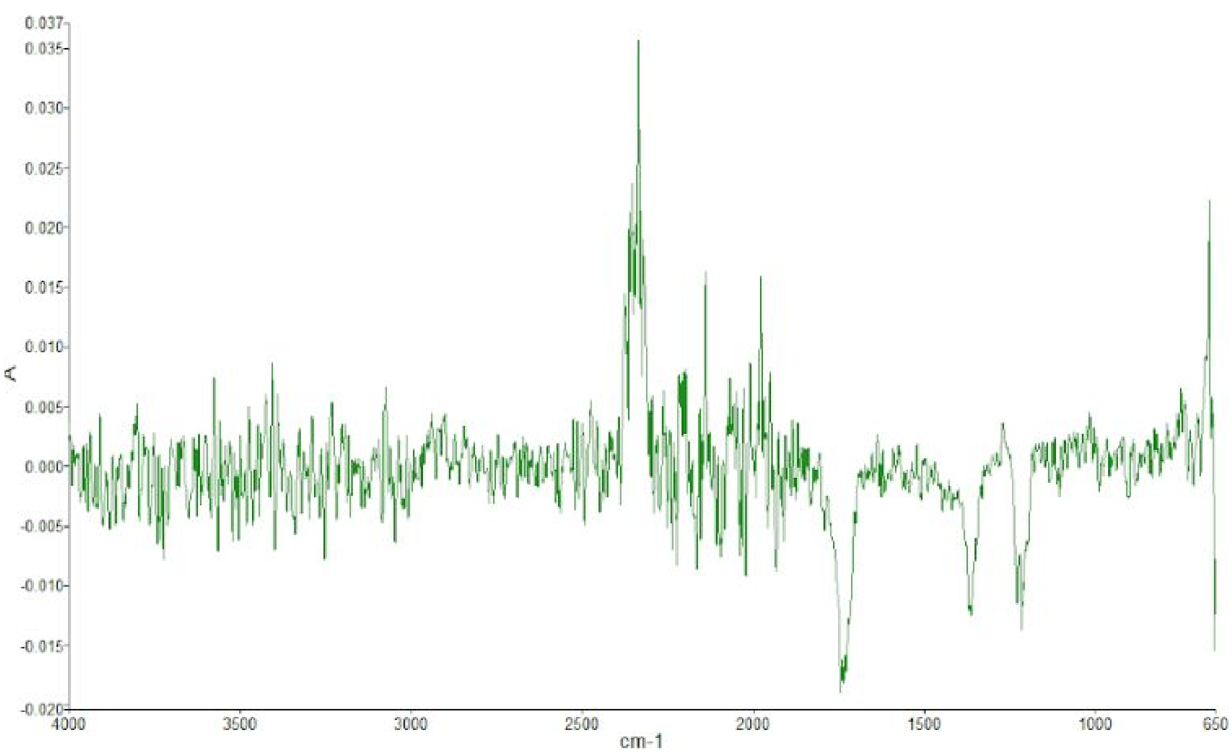
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
-0.005
-0.010
-0.015
-0.020
-0.025
-0.030
-0.034
A
4000
3500
3000
2500
2000
1500
1000
650
cm-1

M/Vs


0.037
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
-0.005
-0.010
-0.015
-0.020
A
4000
3500
3000
2500
2000
1500
1000
650
cm-1

Appendix E: pH and Specific Gravity

Hop Combo	pH	SG (3X10^-4 g/cm^3K)	Temp (F)	Beer Score
Water	6.52	1.0007	71.8	
M/G	4.54	1.0088	50	12
2M/Ce	4.58	1.0091	52.4	12
M/Ce	4.53	1.0074	54.1	10
M/M	4.55	1.0082	55.2	10
2M/2M	4.74	1.0077	51.8	9
2Ci/Ce	4.68	1.0088	53	13
Ci/Ce	4.61	1.009	52	13
2M/G	4.61	1.0087	53	13
Ci/Ci	4.51	1.0083	52	9
4Ci	4.71	1.0086	49.9	12
Combos of 3				
G/Ce/Ci	4.65	1.0098	67.8	10
2G/Ce/2Ci	4.66	1.0095	67.7	10
G/Ce/2Ci	4.72	1.0087	67.7	11
2G/Ce/Ci	4.59	1.0076	68	4
M/G/Ce	4.56	1.0099	68	12
2M/2G/Ce	4.75	1.01	68	9
2M/G/Ce	4.62	1.0087	67.8	9
M/2G/Ce	4.72	1.0085	68.2	5
M/G/Ci	4.63	1.0092	67.2	18

Appendix F: Calculations

Scoring of Each Trial (Good and Bad Scores)

Compounds	Good	Bad
tridecane 1-iodo	1.37	2.75
Heneicosane	4.72	3.26
Undecane	0.58	2.48
Sulfurous Acid	2.29	1.09
Octane 6/5-ethyl-2-methyl	1.31	0
hexane 3,3 dimethyl	2.3	0.59
3-ethyl-3-methylheptane	1.39	2.08
heptane 2,4-dimethyl	0	0.59
hexadecane	3.59	4.48
decane 4-ethyl	6.8	4.48
tridecane 6-methyl	0.72	0.64
eicosane	2.66	4.69
decane 2,3,5 (6) tri-methyl	5.84	3.54
pentadecane	2.22	0.72
heptadecane 8-methyl	0.9	1.73
octodecane	1.58	0.78
Heptacosane	2.34	0.72
dodecane 4,6 - dimethyl	0.72	2.16

To calculate good and bad scores, we first decided a threshold for good and bad. For Budlight, we set this threshold at 50 and for Purgatory's wort, we set it at 60 based on his comments and the overall scores. We then used the results from the GC-MS and in every instance we found the compound we labeled it as good or bad respectively. From this, we then added up all the values to find a total score for good and bad. We did this for each compound that appeared numerous times. An example of our procedure is shown below:

Compound	quality	freq G	freq B	score G	score B
tridecane 1-iodo	0.78 B	2	4	1.37	2.75
	0.72 B				
	0.78 G				
	0.53 B				
	0.72 B				
	0.59 G				