The Effect of Process Changes on the Aging of Light and Dark Beers

A Major Qualifying Project Report
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Abstract

This collaborative project with Purgatory Beer Co. aimed to better understand how variations in the brewing process affect the product shelf-life. Our work focused on improving mixing within the kettle, eliminating the wort sugar wash, and dispersing the hops uniformly in two different beer styles; all focused on better controlling dissolved oxygen content. Minimizing oxygen content and improving hops dispersion appeared to impact the quality of the NEIPA whereas the effect on the porter was less apparent. Additional aging and chemical analysis is recommended following project cessation due to the COVID-19 pandemic.

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1. Introduction

In the last few decades, the number of licensed breweries in America have risen exponentially. With this rise in popularity, came the era of craft beer. Purgatory Beer Co. (Purgatory) in Whitinsville, MA is a microbrewery dedicated to the production of unique craft beer for everyone, from the casual drinker to enthusiasts. They offer a growing range of products, including stouts, brown ales, varieties of India Pale Ales (IPA), and porters.

IPAs are a popular light, and hoppy beer style. Alternatively, porters are a dark beer made from browned malts for a bitter note. The processes of brewing a light versus a dark beer are very similar and can be completed using the same equipment, however the final products are quite different in taste and in their chemical characteristics. Throughout this project, we aim to continue and expand upon research performed the previous year to combine chemistry and processes to determine relationships between process changes, quality, and the shelf life of an IPA and a porter.

Process control is the monitoring of an operation and performing changes as needed to keep variables within a set range. Brewing beer is a fermentation process, and like any other operation, there are factors that can affect the quality of the final product. This means that the control of the fermentation process is based upon measurements of the physical, chemical, and biochemical properties of the material being fermented such as temperature, humidity, pH, pressure, grain size distribution, and malt and barley type and variety. There are three main stages of the brewing process: mashing, brewing and fermentation. Each of these stages involve different variables, which, if not held constant batch to batch can, affect the overall quality of the beer. This is where traditional process control comes into play. Purgatory has process controls in place for some of these factors, however, adding ingredients is still a manual process which leaves risk of variation between batches. The experiments described here were created to express these potential inconsistencies and determine their potential effects.

Due to uncontrollable circumstances, all experimentation and data collection for this project was terminated on March 6, 2020. The spread of the COVID-19 pandemic brought forth WPI and governmental mandates that would not allow for the ethical continuation of the work required by this project. This paper describes all experimentation completed before that date and includes recommendations for future research we had hoped to complete.

2. Background

While beer does not expire, its lifetime is limited by the flavor profile changing with time. While a select few beers take on pleasant sherry aromas with age, the majority follow a general flavor profile such as seen in Figure 1. The initial hoppy bitterness degrades, and a stale cardboard-like flavor emerges, making the beer undrinkable, and therefore, unsellable.

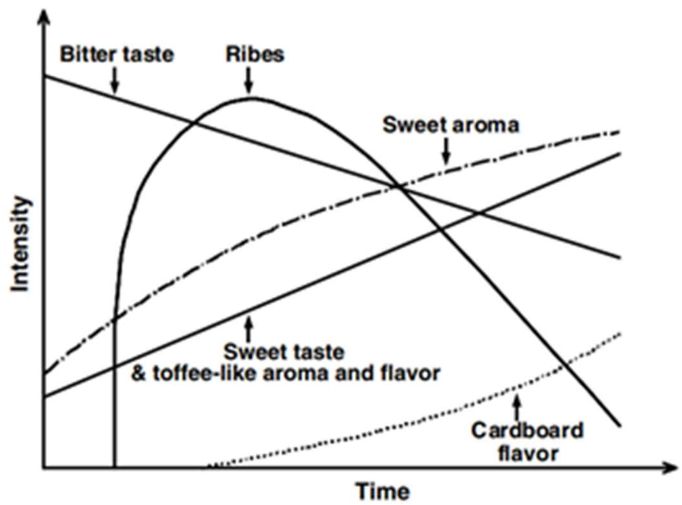

Figure 1: *Diagram of a typical flavor profile of beer throughout its shelf life.*

The bitter aspect of beer is usually a desirable characteristic, while the sweetness varies but is generally kept low. Over time, these flavors and aromas inversely age, changing the product to be sweeter and staler than it was brewed to be. Several reactions could be the cause of this flavor change in any given beer. One such reaction is the oxidation of ethanol, and therefore the level of dissolved oxygen (DO) must be kept to a minimum through careful air purging, tightly sealed final containers, and storage conditions. Other reactions include the Maillard reaction. This creates the Maillard intermediate, Furfuryl alcohol, which then goes through a condensation reaction with ethanol to form Furfuryl Ethyl Ether. If this compound exceeds its allowable threshold, the result is a “solvent-like aroma” and “harsh flavor”. Many other compounds, known as aging markers, have been established by previous studies and emerge or degrade throughout the drink’s shelf life. A partial list of such markers can be seen, along with the associated reaction, in Figure 2.

Aging marker	CV (%)	Aging reaction
3-Methylbutanal	2.67	Strecker degradation, oxidation of alcohol
2-Isobutyl-4,5-dimethyl-1,3-dioxolane	7.19	Cyclic acetal formation of aldehyde with 2,3-butanediol
Furfural	7.01	Maillard reaction
Furfuryl ethyl ether	5.35	Etherification of ethanol and Maillard compounds
Diacetyl	4.97	Maillard reaction
Acetaldehyde	2.16	Oxidation of ethanol
n-Hexanal	6.22	Release of lipid oxidation products in beer
Iso-amyl acetate	5.11	Hydrolysis of esters produced by yeast
Ethyl acetate	5.24	Hydrolysis of esters produced by yeast
Ethyl caproate	1.96	Hydrolysis of esters produced by yeast
Ethyl lactate	5.94	Esterification of ethanol and organic acid
4-Methylpentan-2-one	7.00	Degradation of hop bitter compounds
3-Penten-2-one	7.04	Degradation of hop bitter compounds
Ethyl 2-methylbutyrate	6.01	Esterification of ethanol and organic acid
Ethyl 3-methylbutyrate	7.57	Esterification of ethanol and organic acid

Figure 2: *A selection of typical aging markers in beers and their implications.*

With different styles of beer, different chemical characteristics, aging markers, and therefore, shelf lives can be expected. The scope of this project encompasses one light and one dark style beer in order to compare and contrast these two general categories. We worked closely with Purgatory's Hop Daggr, a New England India Pale Ale (NEIPA), and a chocolate porter recipe. Both categories will experience alcohol oxidation, producing compounds such as 3-Methylbutanal and Acetaldehyde; however, many other markers are more prone to one type than the other. For example, the NEIPA contains a large amount of hops compared to very little in the porter. Hop degradation will be more pronounced in the IPA, therefore, the presence of pentones will be monitored in both, but less likely to appear at a significant level in the porter.

The chemical changes in beer can be monitored through analysis technology such as gas chromatography-mass spectroscopy (GC/MS). GC/MS will simultaneously allow for qualitative and quantitative data collection of the analyte. This involves the liquid-liquid extraction of the beer compounds into a solvent which is then analyzed via GC/MS. This flashes the liquid sample into a mobile gas phase, which separates components within the sample based upon their boiling points. The separated compounds then elute from the GC column at different rates and are ionized as they enter the MS detector. The mass of the fragmented ions are ratioed to their charge (M/Z), which generally represents the molecular weight. This combination analysis allows for the identification and quantification of the various beer compounds. Regular repetition of this analysis will allow us to create a transient chemical profile of our beer samples. This chemical profile can then be interpreted as a flavor profile with the knowledge of the acceptable thresholds of both desirable and undesirable compounds.

Beer is considered highly unstable. This is due to its high risk for contamination during the brewing process and other environmental factors that can change the quality of the beer, ultimately decreasing the beer's shelf life. The most widely known factors for affecting the quality of beer are temperature, light, and oxygen.

Temperature has a major impact on the overall quality of beer, especially when storing the final product. It is commonly known that once beer is refrigerated, it should not be warmed again and returned to the refrigerator as this affects the flavor. When beer is stored at cold temperatures, a haze forms. This haze consists of a reversible association of polymerized polyphenols and proteins, once the beer is brought back to room temperature the haze disappears as the polyphenols and proteins re-dissolve into the beer. If the chilling and warming of the beer is repeated, this haze will become permanent, altering the texture of the product. The haze will also become permanent if the beer is stored at room temperature for too long, this is typically the period of time considered to be the shelf life. Beer that is stored in warmer temperatures have higher amounts of tannoids due to the increased rate of reaction that comes with a higher temperature. Tannoids add an undesirable bitterness to the beer and should be kept to a minimal concentration.

Beer tends to be stored in cans or amber bottles so that light cannot come into contact with the beer. Beer is sensitive to light, especially in the 350-500nm range as these wavelengths can penetrate clear and green glass containers. When light contacts the beer, it develops a skunky flavor, and it is now considered "sun-struck" or "skunked." This is due to a particular hops component. Hops are used in the brewing process to give the beer bitterness and provide aromas to make the beer enjoyable. Hops also suppress certain microorganisms from growing. However, when beer is exposed to light, one of the side chains of the iso-α-acid, a component in the hops, is split and the radical that is released binds with sulfur. This reaction produces 3-methyl-2-butene-1-thiol, or MBT. MBT has one of the most powerful tastes compared to other compounds in beer, which in the case of MBT is a "skunky" flavor.

Oxygen is known to lessen the longevity of beer but is also necessary in the early stages of brewing. Oxygen is required for the proper germination of barley in the malting process and is used by the yeast to manufacture and maintain its cell membrane. It is also essential in the oxidation and polymerization of polyphenolic compounds. Polyphenols are chemical compounds that bring flavor to the beer, some have an off taste while others add desired flavors to the beer. This oxidation process makes the compounds insoluble and helps to give a clarified final product. However, oxygen is detrimental to beer once the finished product is stored and contributes to the deterioration of the beer. Some of the initiatives in the brewing industry are looking into ways to reduce the amount of dissolved oxygen in the final packaged product and to limit the amount of oxygen entering the product through the packaging process. With this in mind, many brewers try to minimize the number of opportunities for oxygen to enter the beer during the brewing process. This is done by minimizing the amount of time the beer, or wort, is exposed to air. Our team wanted to investigate whether any areas of the Purgatory beer brewing process could allow for unnecessary amounts of oxygen to enter the beer. Our team observed a brew day and learned that at the end of the grain steep, Purgatory uses a pump to cycle the wort through the grains for approximately 10 minutes in an effort to extract as much sugar from the grains as possible. In this pumping process the wort leaving the bottom of the kettle enters a pot with a strainer and is then pumped back into the kettle to wash over the grains again. This pot is exposed to the air, and the wort often froths as it hits the strainer, potentially leading to excess oxygen entering the wort.

In this project we explored three changes that could be made to the brewing process of a NEIPA and a porter. For each beer style we performed four brews: a control brew, a well-mixed brew, a "no-pump" brew and a powdered-hops brew. During each brew, with the exception of the no-pump brew, a pump was used to simulate Purgatory's grain washing process. This was to determine if any unnecessary oxygen was entering the beer at this stage and if the pump had a significant impact on sugar extraction. The well-mixed brew was stirred constantly throughout the brewing process in an effort to maintain a constant temperature throughout the kettle. The powdered-hops brew was identical to the control with the exception of the form of the hops when added to the wort; a fine powder rather than in pellet form to test the effect of size distribution.

3. Methodology

Our team knew that we were going to be brewing four alterations of both a porter and an IPA, however, our first two objectives were to practice and observe a brew day, as we had no prior brewing experience. Our team performed a trial run of brewing an IPA by obtaining a homebrew kit and borrowing equipment from one of the team members' family. This was done so that the team better understood the brewing process and the common brewing mistakes were discovered and improved upon since consistency was vital to our experiments. From this experience, we learned several valuable lessons that significantly increased our consistency with the experimental brews. Our team then observed a portion of one of Purgatory's brew days to better understand how their equipment works so that our process could better resemble Purgatory's.

3.1 Brewing Process

The NEIPA that was produced in the lab was brewed using one of Purgatory's recipes for Hop Daggr IPA with some slight modifications to better fit the constraints of brewing smaller batches in a laboratory without industrial equipment. Due to time constraints, the porter that was brewed in the lab was a general homebrew kit from Homebrew Emporium in West Boylston, MA with some slight modifications to make the flavor more similar to one of Purgatory's chocolate porters. The following is the general process that was used to brew both the NEIPA and the porter; while the process was nearly identical for these two beers, the differences are discussed as they arise. We obtained the NEIPA hops from Purgatory and purchased the grains, malt, yeast, and all the porter materials at Homebrew Emporium. Most of the equipment used was in the possession of the team members and the other materials needed were obtained from WPI laboratories.

First, a measured quantity of water, 1 gallon for the NEIPA, 1.25 gallons for the porter, was heated to approximately 70ºC in a large pot on a hot plate. Once 70ºC was reached, all of the grains were added to the water and given a small stir to make sure the grains were completely submerged in the water. For the NEIPA, we used malts in solid grain form which were added to the kettle with the grains; while for the porter liquid malt extracts were used and added at a later stage in the brewing process. The grains were then left to steep for 25 minutes. The batch aimed at regulating temperature was continuously stirred during this time to create a well-mixed kettle. At the end of this 25 minutes, the solution in the pot is now wort. Figure 3 below shows the kettle on a hot plate and the grains steeping in the kettle.

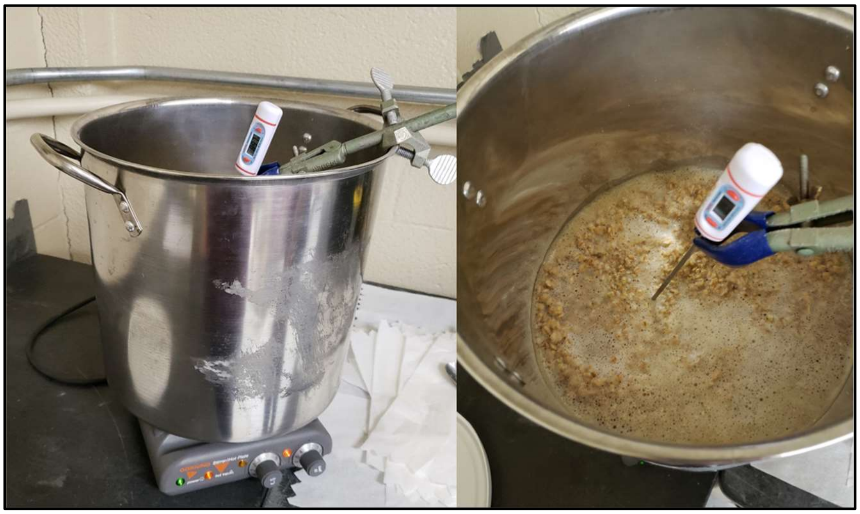

Figure 3: *Brew kettle on a hot plate (left) and the grains steeping in the kettle (right).*

During the grain steeping process for the IPA control and well-mixed brews we made a temperature map of the kettle to determine if continuous stirring had a significant impact on the temperature distribution within the kettle. To do this, we used a temperature probe and recorded the temperature at specific points in the kettle approximately 5 minutes into the grains steeping. This was done at three levels in the pot, the top, middle, and bottom, with care to make sure the thermometer was not resting on the bottom of the kettle, as the temperature of the pot on the hot plate could be hotter than the liquid in the pot itself. At these three levels, the temperature was taken in the middle of the kettle, and at four locations along the perimeter of the pot.

Next the wort was run through a peristaltic pump to simulate Purgatory's process to extract as much sugar as possible. To do this, the wort was poured into a strainer over a bucket. The grains were caught by the strainer and the wort flowed through into the bucket; then a hose was attached to a pump and the wort was cycled back through the strainer for 5 minutes. Due to the size of the strainer and the amount of grains that were used in the NEIPA, this process had to be done twice for each batch so that wort was pumped through all the grains and to make sure they were thoroughly washed. This process is shown in Figure 4 (left) below. The NEIPA and porter batches aimed at limiting oxygen exposure were not put through this step. Our team had intended to run a volumetric study to determine the flowrate of the wort, and the fraction of wort that was pumped through the system, however, due to the COVID-19 pandemic our team was unable to return to the lab to perform this test.

The pot was then cleaned to ensure no grains remained behind, and the wort was returned to the pot, Figure 4 (right), and brought to a boil. As we were using a liquid malt extract for the porter, the malt was poured into the boiling water and stirred so that the malt dissolved and did not stick and burn to the bottom of the pot, the wort was then returned to a boil.

Figure 4: *Peristaltic pump cycling wort through the grains (left). After 5 minutes, the wort is poured back into the clean kettle (right) and returned to the hot plate to bring the wort to a boil.*

Once the wort was boiling, several sets of hops needed to be added. Three hop varieties were added to the NEIPA and two were used in the porter. The hops were then added according to the schedule seen in Table 1. While the homebrew porter recipe provided times appropriate for use at the lab scale, Purgatory's hops schedule had to be altered to accommodate the volume of the brew.

Table 1: *Timing schedule for adding hops to both the NEIPA and the porter.*

NEIPA		**Porter**	
Hop Strain	Time for Boil (minutes)	Hop Strain	Time for Boil (minutes)
Centennial	20	Magnum	55
Citra	5	Willamette	5
Mosaic	5		
Citra	15		
Mosaic	15		
Citra	10		
Mosaic	10		
Citra	12		
Mosaic	12		

As each set of hops were added, the pot was stirred to simulate the whirlpool system that Purgatory uses to make sure the hops are well-mixed throughout the kettle. For the powdered-hops batch of each beer type, all hops were first finely ground, all other brews utilized hop pellets. A comparison of the hop pellets and the crushed hops is shown below in Figure 5.

Figure 5: *Hop pellets, left, vs crushed hops that were added to the powdered-hops batch, right.*

After the last set of hops were added, the unsweetened cocoa powder was added to the porters and stirred into the wort. The temperature of both beers then needed to be brought down so that when the yeast was pitched, they were not killed by the heat. Then the pot containing the wort was placed in an ice bath to bring the temperature down to approximately 22°C, shown in Figure 6. Once this temperature was reached, small amounts of room temperature water were added to the wort and hydrometer readings were taken after each addition to bring the wort to the desired specific gravity. For the NEIPA the wort was brought to a specific gravity of 1.060, and for the porter the specific gravity was 1.052; this is the original gravity (OG) of the beer. Once the wort was at the desired OG, it was then moved to the fermenters. Mason jars with airlocks inserted into the covers served as our fermentation vessels. This ensured that the beer was closed to the air, while the CO_2 that the yeast gave off was able to be released and didn't build pressure inside the jar. The yeast, ~0.02 ounces, was pitched into each jar and the jars were placed in a dark corner of the laboratory to allow them to ferment. Fermentation is complete when CO_2 is no longer actively being released and the beer is within the desired final specific gravity range.

Figure 6: *Porter resting in an ice bath. The pot is placed in a sink filled with ice until the temperature of the wort is brought down to around 72°F.*

An additional step that was taken with the NEIPA that was not with the porter was dry hopping and moving the beer to a secondary fermenter. Moving an IPA to secondary fermenter allows for a clearer final product, especially with homebrews. While Purgatory does not utilize secondary fermenters, it was an extra step that our team had previous experience with and believed would help our final product to achieve a clearer product more similar in quality to Purgatory, without sacrificing too much of our product. Dry hopping is when hops are added to the beer after fermentation has begun to add more hop aroma to the beer. For the dry hopping process, two types of hops were added at the same time, citra and mosaic. The first dry hop took place on day eight of fermentation, this was also when the beer was moved to a secondary fermenter, a new mason jar, shown below in Figure 7.

Figure 7: *The dry hopping process for the NEIPA's control and well-mixed brews. After 8 days of fermentation, the beer is moved to a secondary fermenter and a specific amount of mosaic and citra hops are added to the beer.*

A second round of dry hopping started on day 10, shown below in Figure 8, and the dry hop ended on day 15. The hops float on top of the beer and as the beer ferments, the hops settle out and fall to the bottom of the fermenter. The beer was then moved to a clean mason jar.

Figure 8: *Second dry hop for the powdered-hops brew. On the left shows the hops floating on top of the beer and on the right shows the crushed hops from the top of the jar.*

Once the beer was done fermenting, the mason jars were moved to a refrigerator to allow the hop solids to settle out, giving greater clarity. For this part of the process, the lids with the airlocks were removed and normal mason jar covers were used. After a short resting period, the beer was taken out of the refrigerator, moved to new mason jars to leave as much sediment behind as possible, and a sugar and water mixture was added to each mason jar. The sugar was added so that the trace yeasts left in the beer would ferment slightly more to bring the carbonation to a suitable level for consumption. Figure 9 compares how the appearance of the NEIPA control changed with each of these relocations. Note that the left and middle photos were taken in the lighted refrigerator, while the right photo was taken on the darker bench.

Figure 9: *When the beer was moved to the refrigerator after fermentation all the hops still floating in the beer settled to the bottom of the jar (left). After the beer was moved to a new mason jar the beer was placed back in the refrigerator for 1 day to rest (center). Then a sugar water mixture was added to the beer and the remaining yeast in the beer would ferment slightly more to carbonate the beer. Photo on the right shows the beer after it has been carbonated.*

The procedure described above was the brewing process for the control batches of the NEIPA and porter. A control allows for comparisons to be made with each of the experimental groups and to see if any of the changes that were made had an impact on the final product. In this experiment, three alterations were made to the control. These batches were the no-pump brew, the well-mixed brew and the powdered-hops brew. In each alteration the same process was followed, as described previously, with only one change made per batch. These alterations were identical for the NEIPA and the porter. For the no-pump brew, the pump system that was used after the grain steep was removed as it was hypothesized that this step of the process could allow for excess oxygen to enter the system as there was some frothing and churning at the bottom of the pot as the wort was pumped through the strainer. The removal of the pump aimed to minimize oxygen entering the system and to determine if this had an impact on the final product. In the well-mixed batch, the change that was made from the control was to have continuous stirring throughout the brewing process. In the control, the only mixing that occurred was when the grains were added to the 70ºC water, when the liquid malt was added to the porter and when the hops were added. In this alteration there was constant mixing during every stage of the brewing process until the ice bath, with an occasional stir to make sure the wort was evenly mixed as it cooled. With constant mixing there is a more even heat distribution throughout the pot and this alteration was done to see if an even heat distribution would have an impact on the brew. The last alteration was the powdered-hops brew. In this brew the hops were not added to the wort in pellet form as they typically are, instead the hop pellets were crushed to a powder. This was done to see if the hops dispersal and the size of the particles in the wort had an impact on the brew.

3.2 Analytical Processes

The aforementioned methods include the steps of experimentation we were able to complete prior to the early termination of work. The following are procedures for the work we had not fully completed. These have been included to better demonstrate the full intent of this project.

To determine the quality of the product, sensory testing would be completed weekly for six to eight weeks or until the beer was determined to be unsellable. However, our team completed only one round of sensory testing prior to the COVID-19 pandemic. This aging study would include visual observation, aroma, taste and the overall experience of consuming the product. The template used to assist this sensory analysis can be found in Appendix C. The visual qualities observed included the color and clarity of each beer; aromatic analysis tested the smell strength and pleasantness. The taste data included many categories such as bitterness, alcohol detectability, and smoothness as well as the overall flavor. The mouthfeel was ranked on the basis of texture and carbonation level. Any off flavors, aftertaste or other comments were also noted before the product was determined to be sellable or not. This process was to be repeated by a set testing team for each product until the beer was deemed unsellable. Beer would be deemed unsellable if the appearance were to make it unappealing to a buyer, or the flavor were to change to an unpalatable taste.

In order to chemically analyze the completed beer products, we intended to utilize GC/MS. To do this the beer must first be extracted into a solvent, as the GC cannot process an aqueous solution. Dichloromethane (DCM) was chosen as the solvent for its low boiling point and stability. We would use equal parts DCM and beer, with 30% weight of NaCl as a drying agent. The mixture is prone to emulsion and therefore was to be slowly spun at approximately 1500 rpm in a centrifuge for one hour. The DCM would then be pipetted into a GC vial with a re-sealing cap. This vial is then placed into the GC/MS queue, ready for analysis. We recognize some limitations to GC/MS analysis include not all of the compounds being extracted into the solvent, and some may decompose at the high temperature of the GC. However, the compiled results of running this GC/MS test weekly until the sensory analysis deemed the product unsellable would allow for an aging profile to be drawn and benchmarks of aging markers to be determined. If the compound's benchmark is surpassed, an aging reaction will have proceeded to a point where the result is detectable within the flavor of the beer and the product is no longer palatable. If these benchmarks differ between brewed varieties of the NEIPA and porter, we can determine if any of our process changes provided a more chemically stable product.

An additional study we had anticipated performing was an accelerated aging experiment. This would mimic the final product not being properly stored or transported, such as being moved to a final location in an unrefrigerated truck. To do this, canned products would be placed in a water bath and slowly warmed to 38°C. The bath would be maintained at approximately 38°C for 6, 12, and 24 hours for three separate trials. These three cans, and a continuously refrigerated can, would then be removed from the bath, opened, extracted into DCM using the same methods as above, and run through the GC/MS. Any discrepancies between the four samples would be noted, and the levels of detectable aging markers would be compared to their benchmarks as determined by the previous aging study.

4. Results

Many results were observed both during and after the fermentation process. These include physical data, such as the temperature distribution within the kettle, sensory data, such as the smell and taste of the products, and chemical data given by GC/MS analysis.

4.1 Physical Data

A temperature map was made of the kettle for both the NEIPA control and well-mixed brew to determine if continuous stirring had an impact on the temperature distribution within the kettle. When compared to the well-mixed, the control showed a wider range of temperatures from bottom to top and positionally at the same level in the pot. The temperature map of the control is shown below in Figure 10. At the center of the kettle the temperature changed from bottom to top of the kettle from 80ºC to 91.7ºC to 70ºC. At the bottom of the kettle, the outer edges ranged from 68ºC to 73.5ºC. At the middle of the pot the edges ranged from 67ºC to 68.6ºC, while at the top of the kettle the edges ranged in temperature from 61.2ºC to 65.7ºC. The widest temperature variation occurred when going from the bottom center of the pot to the top center of the pot, a change of 21.7ºC. The smallest temperature variation was at the top of the pot with a range of 61.2ºC to 70ºC, an 8.8ºC difference. Overall, the control had a temperature variation throughout the entire kettle of 30.5ºC from a range of 61.2ºC to 91.7ºC.

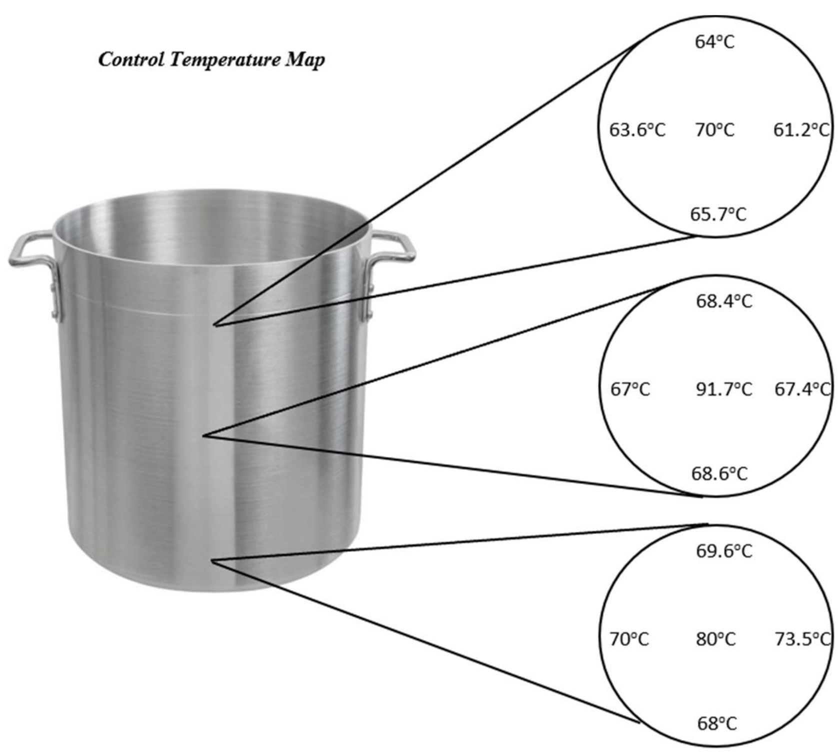

Figure 10: *Temperature Map of the NEIPA Control approximately 5 minutes into the grain steep time.*

For the well-mixed alteration, the temperature ranges were much smaller than in the control, shown below in Figure 11. From bottom to top, the center of the kettle, the temperature changed from 83.5ºC to 79.5ºC to 75.4ºC. The bottom edges of the kettle temperatures ranged from 72.3ºC to 74.8ºC. The middle edges of the kettle ranged from 72ºC to 73.2ºC while the top edges ranged from 68.3ºC to 71.2ºC. This gave an overall temperature range in the kettle from 68.3ºC to 83.5ºC, a total difference of 15.2ºC.

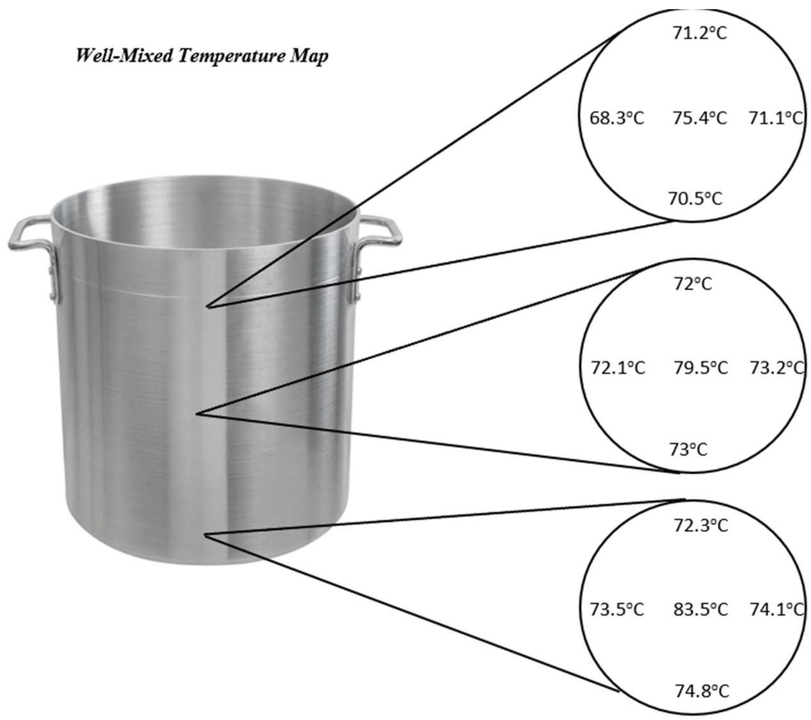

Figure 11: *Temperature Map of the NEIPA Well-Mixed alteration about 5 minutes into the grain steep.*

The temperature difference was approximately half in the well-mixed kettle than in the control, meaning the temperature distribution was reduced by the constant stirring. Additionally, the hottest point in the control kettle was the center at the middle of the pot while for the well-mixed alteration the hottest point was the center at the bottom of the pot. These differences in the temperature maps for these two brews show that continuous mixing has a significant impact on the temperature distribution of the brew kettle.

As the four NEIPA batches fermented, there were significant differences in appearance as time went on. For the different brews, the day each variant was brewed was considered Day 0 for that specific brew, shown below in Table 2.

Table 2: Brew dates for the NEIPA variants.

NEIPA Variant	Day 0 Date
Control	February 1, 2020
Well-mixed	February 1, 2020
No-pump	February 4, 2020
Powdered-hops	February 5, 2020

While these batches were brewed on different days, comparison photos show the same day of the fermentation process for each alteration, not the same calendar day. This allows a direct comparison to be made for each alteration. Day 1 for each alteration is shown below in Figure 12. On day 1, a lot of sediment, or trub, from the brew starts to settle at the bottom of the fermenter. Across the alterations there are varying levels of clarity of the fermenting beer. The control is amber in color, with greater clarity than the other three alterations. The well-mixed and no-pump are light brown in color, while the powdered-hops alteration has a green hue. Each alteration has varying levels of foam on top of the beer indicating that fermentation has begun.

Figure 12: *Day 1 for each of the NEIPA variations. From left to right: control(3), well-mixed(3), no-pump(2) and powdered-hops(3).*

On Day 8, each alteration was moved to a secondary fermenter to leave as much sediment behind as possible and improve clarity at the end of the process. This was also the day that the first set of dry hops were added. The photos shown below in Figure 13 are before the beer is moved to a secondary fermenter and the dry hops were added. In the powdered-hops photo, it can be seen that the hops are starting to settle out of beer as there is a layer of solids about an inch down the jar that appears to be floating.

Figure 13: *Day 8 for each of the NEIPA variations. From left to right: control, well-mixed, no-pump and powdered-hops.*

On Day 10, the second dry hop was added to the beer. The photos shown below in Figure 14 are from just before the second set of hops were added. In each alteration there is a green layer on top of the beer, this is the hops as they have become saturated. In the powdered-hops brew the hops are brighter green in color than in the others. There is also a small amount of sediment that has started to settle out again at the bottom of the fermenters.

Figure 14: *Day 10 for each of the NEIPA variations. From left to right: control, well-mixed, no-pump and powdered-hops.*

Day 15, as seen in Figure 15, shows each of the alterations darkening and improving in clarity, yet the well-mixed alteration remains a murky, light brown. Each alteration has a green foam, which is a mixture of foam produced by fermentation and the hops dissolving as they sit on top of the beer. They are almost done fermenting. To see more side by side comparisons, see Appendix A.

Figure 15: *Day 15 for each of the NEIPA variations. From left to right: control, well-mixed, no-pump and powdered-hops.*

In addition to the differences in appearance from alteration to alteration, there were also significant differences within each alteration as fermentation proceeded. To show the progression of how the NEIPA alterations ferment, Figure 16 shows the NEIPA control over the course of its fermentation period. In order from left to right, Days 1, 3, 6, 8, 10, 14, 20 and the final product are displayed. Day 1 shows a lot of sediment at the bottom of the fermenter with the beer a light amber color. As fermentation proceeds, more hops settle out of the beer, providing clarity and the amber color deepens.

Figure 16: *The progression of the NEIPA control on Days 1, 3, 6, 8, 10, 15, 20 and the final product.*

The progression of the NEIPA well-mixed alteration, Figure 17, shows a different change in appearance over time than the control. Day 1 shows a large amount of sediment settling out, the beer is a tan color. Days 3-10 show the beer developing a very cloudy appearance and turning a lighter brown. As the dry hop continues, Days 15 through 19, the beer starts to darken, while still maintaining a cloudy appearance. The final product is still quite cloudy, and light brown in color.

Figure 17: *The progression of the NEIPA well-mixed alteration on Days 1, 3, 6, 8, 10, 15, 19 and final product.*

The progression of the NEIPA no-pump alteration is shown in Figure 18. This alteration starts as a cloudy, light brown color. As fermentation proceeds it maintains this color until the end of fermentation, where on Day 15 it develops a cloudy, dark amber color as the hops settle out. The final product is a darker amber color than the control.

Figure 18: *The progression of NEIPA no-pump alteration on Days 1, 3, 6, 8, 10, 15, and final product.*

The progression of the NEIPA powdered-hops alteration is shown in Figure 19. On Day 1 the beer is cloudy, and brown in color. On Day 3, the beer starts to lighten, while still maintaining its cloudy quality. On Day 15, as fermentation is coming to an end, the beer starts to develop a hazy amber appearance. The final product is a dark amber color, similar to the no-pump alteration.

Figure 19: *The progression of NEIPA powdered-hops alteration on Days 0, 1, 3, 6, 8, 10, 15 and final product.*

The four variants had significant differences in appearance as the fermentation process proceeded. The final products for each of the NEIPA alterations is below in Figure 20. The control was clear and amber, the well-mixed developed a cloudy, light brown color, while the well-mixed and no-pump alterations look similar with a dark yet clear amber color.

Figure 20: *The final product for the NEIPA alterations. From left to right: control, well-mixed, no-pump and powdered-hops.*

Similar to the NEIPA, the porter Day 0 was considered to be the day that alteration was brewed, shown below in Table 3. However, as the four porter alterations fermented, there were not as significant differences in appearance as the NEIPA variants displayed. Another difference between the porter and NEIPA is the amount of time required for fermentation. The NEIPA, while it varied among the alterations, needed approximately 15 days of fermentation; the porter required only 6 days for complete fermentation.

Table 3: *Brew dates of the Porter variants.*

Porter Variant	Day 0 Date
Control	February 19, 2020
Well-mixed	February 20, 2020
No-pump	February 19, 2020
Powdered-hops	February 20, 2020

Day 1 of porter fermentation is shown below in Figure 21. In these photos, each of the porter alterations have a rich brown color. At the bottom of the fermenters, some sediment has settled out and there are varying levels of foam at the top. The no-pump alteration has the most foam while the other three alterations have a minimal amount.

Figure 21: *Day 1 for each of the porter alterations. From left to right: control, well-mixed, no-pump and powdered-hops.*

Day 6 is shown below in Figure 22. There is little variation in appearance from alteration to alteration. The porters have developed a dark brown, almost black, color and there is a brown sediment at the bottom of the fermenters, largely composed of the cocoa powder and some hops.

Figure 22: *Day 6 for each of the porter alterations. From left to right: control, well-mixed, no-pump, and powdered-hops.*

Figure 23 below shows the complete progression of the control, days 0, 1, 2, 6, and the final product. In the early days of fermentation, days 0-2, the sediment slowly settles out, and the beer has a chocolate color to it. As the beer ferments, it turns the dark brown or black color that porters are known for. The last photo shows the final product after it has been carbonated.

Figure 23: *The progression of the porter control on Days 0, 1, 2, 6, and the final product.*

Figure 24 shows the progression of the porter well-mixed alteration on Days 0, 1, 6 and the final product. The well-mixed alteration follows the same progression as the control with the product developing a dark brown or black color as the cocoa solids are removed.

Figure 24: *The progression of the porter well-mixed on Days 0, 1, 6 and final product.*

Figure 25 shows the progression of the no-pump alteration, following the same schedule and progression as the control.

Figure 25: *The progression of the porter no-pump on Days 0, 1, 2, 6, and the final product.*

Figure 26 shows the progression of the powdered-hops alteration, following the same schedule and progression as the well-mixed alteration.

Figure 26: *The progression of the porter powdered-hops on Days 0, 1, 6 and the final product.*

The final products of the porter variants are shown below in Figure 27. The four alterations are nearly identical in appearance, all having developed a very dark brown or black color. While it is not apparent in the photos, in light it was possible to determine there were no visible particulates in any of the products.

Figure 27: *The final product of the porter alterations. From left to right: control, well-mixed, no-pump, and powdered-hops.*

Following the trend seen during fermentation, the final products of the porters were all found to have the same final specific gravity (FG) of 1.014, and therefore, the same alcohol by volume (ABV), while the NEIPAs showed a range of FGs from 1.011 to 1.018. The final ABV of each brew can be seen in Table 4 below.

Table 4: *Percent alcohol by volume of each final product.*

% Alcohol by Volume		
	NEIPA	Porter
Control	6.43	4.98
Well- Mixed	5.51	4.98
No-Pump	6.3	4.98
Powdered-Hops	6.3	4.98

4.2 Sensory Data

At the completion of the fermentation process, the overall quality of each product needed to be determined. While this was meant to be done weekly for six to eight weeks, only one round of sensory testing was completed prior to the early termination of experimentation. The average results of the three key parameters, clarity, taste, and the pleasantness of the smell, are found in Table 5 below. The complete set of data can be found in Appendix D.

Table 5: Average results of key sensory testing parameters.

	NEIPA				Porter			
	Control	Well-Mixed	No-Pump	Powdered-Hops	Control	Well-Mixed	No-Pump	Powdered-Hops
Clarity	Clear	Not Clear	Somewhat Clear	Mostly Clear	Expected	Expected	Expected	Expected
Taste (1-5)	2	3	2	2.1	1.9	1.88	1.88	2.25
Smell (1-5)	1.55	2.75	1.8	1.6	1.25	1.55	1.5	1.55

The NEIPA was expected to be clear and light amber in color. The control matched this description; however, some of the variable batches resulted in clearer products than others. The well-mixed batch was the cloudiest with a hazy finish. The richness in color of the porters were all very similar and appeared as expected. The taste and smell pleasantness were ranked on a 1-5 scale, where 1 is very good, 3 is decent, and 5 is bad. All tastes averaged quite good or better with the exception of the well-mixed NEIPA which was found to be decent. Pleasantness of smell followed a similar pattern as the tastes. The porters scored especially well in this category and the well-mixed NEIPA again received a middling mark of decent.

4.3 Chemical Data

After brewing the eight experimental beer batches, we planned to run GC/MS analysis weekly to build a transient chemical profile as the beer aged. We would then compare the process changes within each beer type as well as the light to dark beer. The changing chemical composition in conjunction with weekly sensory data would have allowed us to determine which reactions and compounds were of the greatest importance in preserving the flavor and aroma of the products. We would then know the time at which aging reaction products would surpass an acceptable level of key compounds. Additionally, we hoped to determine if our process alterations produced a noticeable change in the timeline of these souring compounds. Due to the early termination of data collection, we were unable to draw conclusive results for this aspect of the project. We expect compounds such as 3-Methylbutanal, Furfuryl Ethyl Ether, 4-Methylpentan-2-one, 3-Methyl-butene-1-thiol, and Acetaldehyde would have been included in the resulting list of key aging markers. Prediction charts of the chemical composition over time for an IPA and porter are shown in Figures 28 and 29 below. At day 42 of the predictions, we changed the conditions to simulate the placement of the products in direct sunlight.

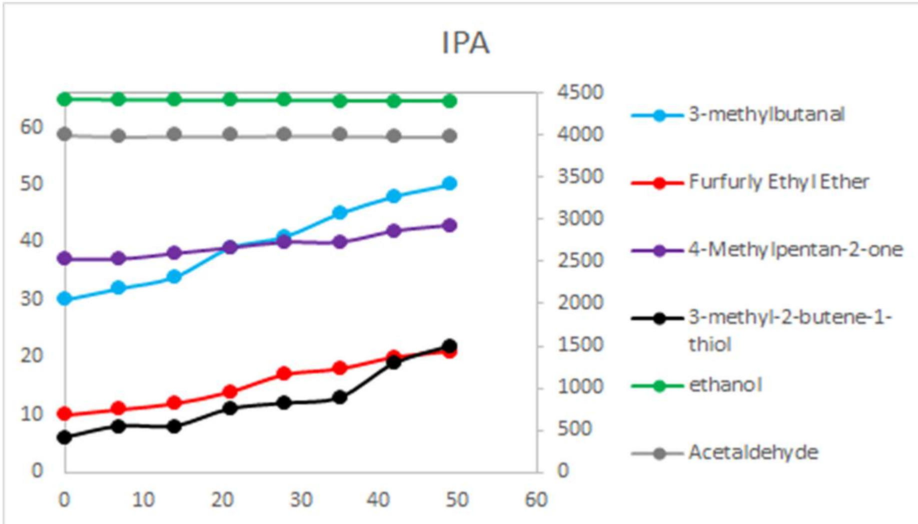

Figure 28: *Predictive aging plot of several compounds in an IPA. Ethanol is plotted in grams; all other compounds are in the unit of micrograms. For scaling purposes, Acetaldehyde is plotted on a secondary axis seen on the right.*

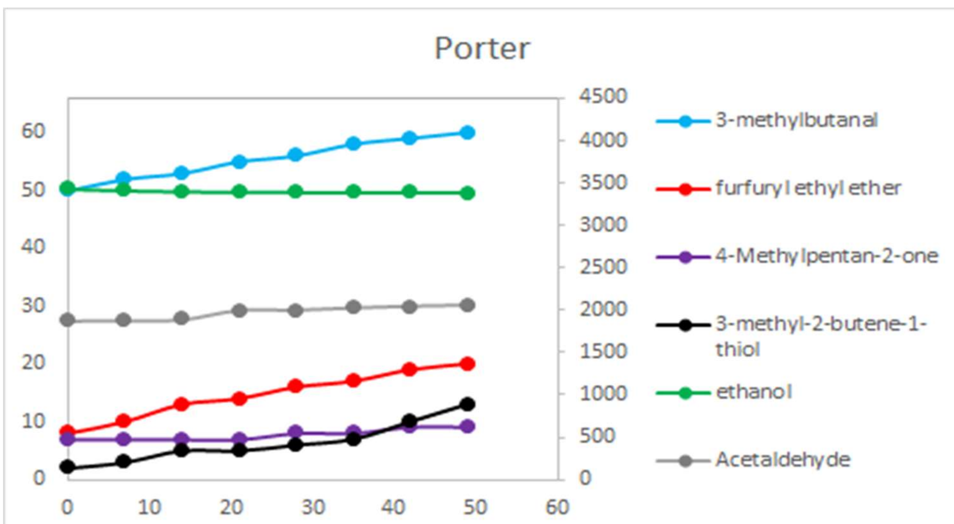

Figure 29: *Predictive aging plot of several compounds in a porter. Ethanol is plotted in grams; all other compounds are in the unit of micrograms. For scaling purposes, Acetaldehyde is plotted on a secondary axis seen on the right.*

These approximations are based strictly on research and not experimental data. However, some of the compounds are known to be higher in a NEIPA than a porter. For example, 4-Methylpentan-2-one is produced by the breakdown of hops. A NEIPA has a far greater concentration of hops than porters, therefore their breakdown will have a more pronounced effect in the product as it ages. Similarly, 3-Methyl-butene-1-thiol is a result of light decomposing a hops component; it is also known to have a very low threshold, beyond which beer becomes undrinkable. Therefore, at day 42 in the predictions, when the product was supposedly exposed to light, there is a greater increase of 3-Methyl-butene-1-thiol in the IPA.

5. Discussion

The experimentation of this project consisted of three variations on two beer recipes. Here we will compare and contrast the resulting brews to evaluate their sensory, quality, and aging data. Additionally, we will acknowledge the limitations we faced and their implications.

5.1 Analysis of Brew Results

The well-mixed NEIPA provided many interesting results. The objective of continuously stirring the kettle aimed to provide an even temperature distribution throughout the entire wort. The temperature map shows that this was successful, and therefore should reduce the risk of burning sugars in hotspots at the bottom of the kettle. However, we also produced a wort with a visibly higher viscosity than any other and a paler, more opaque color. We believe the stirring not only provided a more even temperature distribution but also a more consistent concentration gradient, and therefore, we extracted more sugar from the same amount of grains in the well-mixed brew than the control. This is supported by the sweeter taste that was detected in the final product compared to any other NEIPA. GC/MS analysis would have confirmed this but was unable to be completed. To combat the overly sweet product, constant stirring with less grains may provide a similar taste to the original NEIPA. If so, materials and cost may be conserved. However, the stirring action also broke down the grains creating an emulsion that never fully separated, thus the hazy final product. It is unknown if using less grains to conserve the taste of the product would resolve the color and clarity issues of the well-mixed brew.

The no-pump NEIPA was brewed with the goal of limiting the initial amount of dissolved oxygen in the beer. When the wort is run through the pump, there is frothing that could lead to excess oxygen entering the liquid phase. In theory, removing this step would decrease the amount of dissolved oxygen in the beer. GC/MS data would have confirmed whether there was a significant impact on DO. Ultimately, our team does not believe that removing this step significantly reduced the DO levels in the beer as oxygen is only sparingly soluble in water. It is unlikely that a statistically significant amount of oxygen would have entered the beer during the small period of time the pump is run. Another impact that removing the pump step could have had on the beer is less sugar in the wort, since the purpose of the pump is to extract as many sugars as possible from the spent grains. A wort that has less sugar would lead to a beer that has a lower alcohol content, however, since the alcohol content of the no-pump alteration was 6.3% and was 6.43% for the control, we cannot conclude that this is true. A 0.13% difference is not significant enough to draw a conclusion that there may have been less sugar in the no-pump alteration without other evidence, such as GS/MS data, as this difference could also be due to incomplete fermentation. Therefore, it remains unknown if the removal of the pump led to significantly less sugar or DO in the wort. The no-pump alteration was significantly different in appearance than the control, which was unexpected. The control had a clear, light amber color while the no-pump alteration was a dark amber color. If there was in fact less dissolved oxygen, that should not have had an impact on the color of the beer. It is suspected that this was due to the grain ratios. When the grains were purchased from Homebrew Emporium, the majority of our grains were combined into one large bag. In the large bag was 6 lbs of pale malt, 3 lbs of white wheat malt and 1 lb of carafoam. Since we were not able to effectively separate the mixed grains, our solution was to create a homogenous mix of grains and measure out the appropriate weight needed for each alteration from the large bag. At the time, no significant impacts were foreseen, however if the mixture was not perfectly homogeneous this may be the source of the color differentiation between the control and the no-pump alteration.

The powdered-hops NEIPA had a very similar result in appearance to the no-pump NEIPA, while it was not as similar to the control as expected. The theory of crushing the hops for this alteration was based on the importance of grain size distribution on brew quality. If the grains should have a uniform size distribution, do hops need this too? Hops typically come in pellet form, but as the control was brewed it was noticed that each of the hop pellets drastically differed in size and density. Some of the hops that were used for the NEIPA were concentrated, therefore, a concentrated hop pellet of the same size as a standard pellet would weigh twice as much. This also means that the surface area of the hop that is in contact with the beer is much less per unit of mass than a standard pellet. The hops were crushed into a uniform powder to determine if there was an impact of size distribution on beer quality. After experimentation, our team suspects that hops with a uniform size would have little to no significant impact on the final product since the hop pellets break up over time in liquids. As for the unexpected difference in appearance from the control, we believe that this was due to a similar reason as believed for the no-pump alteration, especially since the powdered-hops alteration is nearly identical in appearance to the no-pump. Since the no-pump and powdered-hops alterations were the last two to be brewed, it would make sense that the bottom of the grain bag had less of one grain type and more of another.

The porters as a whole showed far less variability throughout the entirety of their fermentation processes and in their final products. The nature of our experiments were to alter how various ingredients were incorporated into the brewing process and determine the effects of these changes. As the quantity of ingredients were far less in the porters than the NEIPAs, we believe this mitigated any effects of the changes. However, liquid malt extracts were used for the porters and solid malts for the NEIPAs. If the same form of all ingredients had been available for both beers, the result of the porters may have been of a more similar magnitude to the NEIPAs. The best example of the results differing between the NEIPAs and the porters is the well-mixed batch for each. While we believe the constant stirring had both pros and cons associated with it, the well-mixed NEIPA was deemed unsellable on the basis of both visual quality and product taste; yet the well-mixed porter was a viable product. For a product to be worthy of sale, it must create an overall enjoyable experience for the consumer. This includes the color, clarity, smell, and taste, among other factors. While the well-mixed NEIPA failed almost every aspect of this test, the well-mixed porter performed nicely. This is the most extreme example of the NEIPA providing significant results when the porter did not.

5.2 Equipment and Limitations

As with any experiment, there were limitations based upon the equipment available to us, especially as we were working on a small scale. One of the major limitations faced was the heating element. In a brewery, there are large kettles that have heating elements that are able to efficiently heat or cool the kettles to the desired temperature and maintain them. Water inlet temperatures are also closely regulated. Since we were working in a laboratory, we used hot plates to heat our pots. During the course of our experimentation we used two hot plates in an effort to be time efficient on the days we were brewing two alterations. One of the hot plates also had a magnetic stirring option, which was needed for the well-mixed alterations so that the mixing was continuous and at the same rate throughout the brew. However, it was discovered that these two hot plates varied in the rates at which they came to temperature. The hot plate with the stirring option took much longer to heat up and did not reach as high of temperatures as the other. We also do not know what temperature these hot plates operated at. One of the plates only had an arbitrary temperature range of minimum to maximum, with no numbers, while the other gave a likely inaccurate temperature. We also had limitations when cooling the wort. At Purgatory, a heat exchanger is used to swiftly bring the wort down to the desired temperature. We did not have the capability of utilizing such equipment and used an ice bath, which is much less efficient. Another limitation was the water quality. We were using the water available from the lab, but we did not test it for alkalinity or undesirable compounds. This could lead to different quality in the final product, as alkaline water tends to produce beer with a lingering aftertaste. However, as we used the same water source batch to batch, there should not be an impact when comparing beer brewed with the same water.

6. Recommendations

Due to the COVID-19 pandemic, and the premature termination of the project, many important tasks were left incomplete. Throughout our experimentation, we also discovered several factors we would consider were further work to be done. Here we discuss objectives we had hoped to accomplish and now will recommend to future students who may wish to continue upon our work.

6.1 Work Continuation

Our first recommendation for future work is the continuation of the aging study. Process changes can result in either a far better or unsellable product, and the changes we made will have no conclusive results until the aging study is performed. Comparing the variants of the light and dark beer over time will determine if they age differently. This will provide information on how NEIPAs and porters may need different brewing or storing conditions in order to extend their shelf lives as long as possible. Additionally, the study will deliver concrete thresholds for key aging markers, beyond which the compounds have such a pronounced effect that the beer is no longer able to be consumed. Each aging marker is the result of a different reaction within the beer. Knowing which reactions are critical for the NEIPA compared to the porter may provide information on how to produce and store the products as different conditions can slow various reactions. The methods to completing this aging study have previously been described, and we believe the results will be significant when carried out.

Additionally, we recommend an accelerated aging study. This would reveal any risk of improper transportation of the final goods. While products are often stored in climate controlled environments, the shipment between the brewery, cannery, and warehouse or seller poses greater risk of conditions that may shorten the shelf life of the beer. Shipping containers, if not refrigerated, can become very warm; mimicking this scenario and performing GC/MS analysis would show if the high temperatures alter the aging plots that were previously described.

6.2 Additional Proposals

In addition to continuing on the aging study, we recommend sampling and testing each wort. This would have given us valuable information on the immediate effect of each of our alterations. It was noticed when we brewed our NEIPA well-mixed alteration that the wort was more viscous and a paler, more opaque color than the others. It was hypothesized that this was due to a higher sugar concentration, but this was not confirmed by GC/MS. The GC/MS results of the wort would also indicate whether there was an immediate impact on DO in the no-pump variant as compared to the control and could serve as a baseline for the aging study.

Another recommendation is to reduce the mass of grains used for the well-mixed variation. Both well-mixed alterations were overly sweet, with the NEIPA resulting in a cloudy product, likely due to emulsified grain solids. We believe that this variant had higher sugar extraction, and therefore, the amount of grains could be decreased to achieve the amount of sugar in the control.

With less grains used, materials are conserved which decreases the cost per brew. We believe the best test for this would be to directly compare varied amounts of grains within a well-mixed process.

While our team did create a temperature map of our own brew pot for the NEIPA control and well-mixed, we also suggest a temperature map be done on Purgatory's kettle. Our small scale temperature maps from the lab may produce different results than the industrial kettle. This may be valuable data to Purgatory to see how well their brew kettle maintains and distributes heat throughout the wort or if they are at risk of burning sugars in hot spots.

The carbonation of beer is a natural process that occurs when priming sugar is added to condition the beer for bottling. Once the beer is bottled and has an airtight seal, the residual yeast in the beer will use the sugar and carbonate the beer over a span of time around two weeks. Many breweries, and even home brewers, do not want to wait this period of time for the beer to carbonate naturally so force carbonating is done by injecting carbon dioxide directly into the beer from a gas cylinder. Our team recommends force carbonating the beer, as this will save the team approximately two weeks that would normally be spent waiting for the beer to finish brewing.

7. Conclusions

The COVID-19 pandemic led to the premature termination of this project on March 6, 2020. This left many important aspects of the project incomplete, with that in mind our team tried to make the best of the situation with many recommendations for any future team that may want to continue our work. The goal of this project was to look at how light and dark beers age differently and to determine if process changes had an impact on how the beers age. The process changes that were made were continuous stirring throughout the brew (well-mixed), the removal of the wort circulation through a pump that Purgatory uses after their grain steep (no-pump), and powdering the hops rather than adding them in pellet form (powdered-hops). These three alterations were brewed in addition to the control for both a NEIPA and a porter.

Our team found that as the four NEIPA alterations fermented, there were greater differences in appearance variant to variant than there were for the four porters. This was seen throughout the fermentation processes and in the final products. The NEIPA control was a clear, amber color, the well-mixed NEIPA was a cloudy light brown, while both the no-pump and powdered-hops alterations were a dark, yet clear, amber color. Not only were there differences in appearance among the four variants, but also differences in taste and smell. The well-mixed variant was overly sweet, while the no-pump beer was described as tasting more bitter. On the other hand, the porters displayed no differences in appearance and very little difference in taste and smell.

The variations that were made to the brewing process in this project had much less of an impact on the porters than it did on the NEIPA. We attribute this to the amount of ingredients that are used in the different beer styles. The NEIPA recipe that was followed in this experiment was a double IPA; this means that twice the amount of grains were needed than are used in a standard IPA, or a porter, recipe. The amount of grains and malts are increased so there is more sugar in the wort, yielding a higher alcohol content in the final product. As the process changes manipulate how the ingredients are incorporated, the beers with more ingredients, and therefore, a higher alcohol content, are more susceptible to variability in the final product if their brewing process is not consistent. Further studies as to the nature of the aging processes will determine if these process changes cause long term effects in the final products.

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Appendices

Appendix A
Fermentation photos by day

A.1: IPA
Day 1

Day 3

Day 4

Day 6

Day 8

Day 10

Day 11

Day 15

Final

A.2: Porter

Day 1

Day 6

Final

Appendix B

Procedure for Beer extraction into Dichloromethane

Materials Needed:

- Beer
- Dichloromethane, DCM
- (2) Graduated Pipette
- Centrifuge tube (50mL)
- Salt
- Balance
- Centrifuge
- GC vial with re-sealing cap

Procedure:

Step:	
1	With a graduated pipette, measure 10mL Beer and place in centrifuge tube.
2	With a graduated pipette, measure 10mL DCM and place in centrifuge tube.
3	On zeroed balance, weigh 3g salt and place in centrifuge tube.
4	Close and label centrifuge tube for appropriate sample.
5	Place sample in centrifuge and spin at 1500rpm for 60min to allow for maximum extraction. If sample emulsifies, repeat steps 1-4 and lower rpm.
6	Remove DCM with pipette and place in GC vial. Seal and label.
7	Your sample is ready for GC/MS analysis.

Appendix C
Sensory Analysis Template

Beer Name:
Tasting Date:
Taster:

Visual Analysis:

Clarity: Clear / Not Clear
Color:

1	2	3
lighter	normal	darker

Aromatic Analysis:

Smell (Strength):

1	2	3
Very little smell	some smell	strong smell

Smell (Pleasantness):

1	2	3	4	5
very pleasant	moderately pleasant	neutral	slightly unpleasant	very unpleasant

Basic Tastes:

Taste:

1	2	3	4	5
very good	pretty good	decent	not very good	bad

Bitterness:

1	2	3	4	5
not bitter	slight bitterness	moderate	very bitter	too bitter to drink

Alcohol:

1	2	3	4
can't taste it	slight taste	some taste	strong taste

Flavor:

1 2 3

strong flavor some flavor little/no flavor

Smoothness:

1 2 3

very smooth somewhat smooth not very smooth

<u>Mouthfeel:</u>

Texture:

1 2 3

thicker than expected expected thinner than expected

Carbonation:

1 2 3

bubblier than expected expected less bubbly than expected

<u>Any off flavors:</u> yes / no

If yes, describe:

<u>Aftertaste:</u> yes / no

If yes, describe:

<u>Summary:</u>

Palatable? yes / no

Sellable? yes / no

Appendix D

Sensory Analysis Results

Sensory Analysis Data: Beer: NEIPA, Taste Tester #1

3/6/2020	**Control**	**Well-Mixed**	**No-Pump**	**Powdered-Hops**
Visual Analysis				
Clarity	clear	Not clear	Somewhat clear	Clear
Color (1-3 scale)	2 (light amber)	1.5 (murky)	2	2
Aromatic Analysis				
Smell Strength (1-3 scale)	2.5	2	2	2.5
Smell Pleasantness (1-5 scale)	1.5	3	2	1.5
Basic Tastes				
Taste (1-5 scale)	2	3	2	2.2
Bitterness (1-5 scale)	3.5	2	3.5	3.5
Alcohol (1-4 scale)	3.5	2	3.2	3.2
Flavor (1-3 scale)	1.2	2.2	1.5	1.5
Smoothness (1-3 scale)	1.2	1.5	1.5	1.8
Mouthfeel				
Texture (1-3 scale)	2.2	2.5	2	2
Carbonation (1-3 scale)	2	2	2	2.2
Any off flavors?	No	Yes, very sweet	No	No
Aftertaste?	Yes, a little bitter but not bad	Yes, but very little	Yes, slightly bitter but not bad	Yes, hoppy/bitter and makes mouth feel dry

Summary				
Palatable	Yes	Yes, but just barely	Yes	Yes, kind of a crisp taste
Sellable	Yes	No, it is not clear and is very sweet	Yes	Yes

Sensory Analysis Data: Beer: NEIPA, Taste Tester #2

3/6/2020	**Control**	**Well-Mixed**	**No-Pump**	**Powdered-Hops**
Visual Analysis				
Clarity	Clear	Cloudy	Somewhat clear	Fairly clear
Color (1-3 scale)	2 (light amber)	1.5 (lighter)	1.9	2
Aromatic Analysis				
Smell Strength (1-3 scale)	2.5	1.75	2.2	2.5
Smell Pleasantness (1-5 scale)	1.6	2.5	1.6	1.7
Basic Tastes				
Taste (1-5 scale)	2	3	2	2
Bitterness (1-5 scale)	3.5	2	3.75	3.25
Alcohol (1-4 scale)	3.2	2	3	3.2
Flavor (1-3 scale)	1.5	2.25	1.3	1.25
Smoothness (1-3 scale)	1.5	1.75	1.6	1.2
Mouthfeel				
Texture (1-3 scale)	2	2.25	1.6	2

Carbonation (1-3 scale)	2	2	2	1.75
Any off flavors?	No	Yes, sweet	No	No
Aftertaste?	Yes, hoppy	Yes, very little	Yes, hoppy, bitter	Yes, sharp flavor
Summary				
Palatable	Yes	Yes	Yes	Yes
Sellable	Yes	No	Yes	Yes

Sensory Analysis Data: Beer: Porter, Taste Tester #1

3/6/2020	**Control**	**Well-Mixed**	**No-Pump**	**Powdered-Hops**
Visual Analysis				
Clarity	Expected	Expected	Expected	Expected
Color (1-3 scale)	2	2	2	2
Aromatic Analysis				
Smell Strength (1-3 scale)	2.5	2.5	2.5	2.5
Smell Pleasantness (1-5 scale)	1	1.5	1.5	1.5
Basic Tastes				
Taste (1-5 scale)	2	2	2	2.5
Bitterness (1-5 scale)	3	3.5	3.8	3.5
Alcohol (1-4 scale)	3	3	3	2.8
Flavor (1-3 scale)	2.2	1.5	2 (little less coco)	2

Smoothness (1-3 scale)	2	1.8	2	1.8
Mouthfeel				
Texture (1-3 scale)	2	1.8	2	2
Carbonation (1-3 scale)	1.5	1.5	1.5	2.3
Any off flavors?	No	No	No	No
Aftertaste?	Yes, not what expected (bitter)	Yes, sweet	Yes, sweet but not as much as the well-mixed one	Yes, sweet but bitter
Summary				
Palatable	Yes (tastes very different than it smells)	Yes	Yes	Yes
Sellable	Yes	Yes	Yes, with the control I couldn't place sweetness but this one I can	Yes

Sensory Analysis Data: Beer: Porter, Taste Tester #2

3/6/2020	**Control**	**Well-Mixed**	**No-Pump**	**Powdered-Hops**
Visual Analysis				
Clarity	Expected	Expected	Expected	Expected
Color (1-3 scale)	2	2	2	2
Aromatic Analysis				
Smell Strength (1-3 scale)	2.5	2.4	2.5	2.4

Smell Pleasantness (1-5 scale)	1.5	1.6	1.5	1.6
Basic Tastes				
Taste (1-5 scale)	1.8	1.75	1.75	2
Bitterness (1-5 scale)	3	2.25	3.2	3
Alcohol (1-4 scale)	2.75	2.75	3	2.7
Flavor (1-3 scale)	2.25	1.75	2	2
Smoothness (1-3 scale)	1.6	1.25	1.75	1.5
Mouthfeel				
Texture (1-3 scale)	2.2	1.8	2	2
Carbonation (1-3 scale)	2	2	1.7	2.25
Any off flavors?	No	No	No	No
Aftertaste?	Yes, light bitter taste	Yes, a little sweet, cocoa	Yes, little bitter, cocoa	Yes, cocoa
Summary				
Palatable	Yes	Yes	Yes	Yes
Sellable	Yes	Yes	Yes	Yes