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Brewing as a Comprehensive Learning Platform in Chemical Engineering

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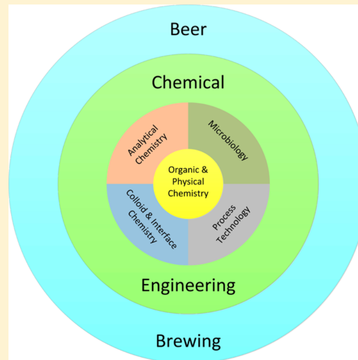
Ⓢ *Supporting Information*

ABSTRACT: Chemical engineering is mostly taught using traditional classroom teaching and laboratory experiments when possible. Being a wide discipline encompassing topics such as analytical chemistry, process design, and microbiology, it may be argued that brewing of beer has many relations to chemical engineering topic-wise. This work illustrates how brewing of beer on a pilot scale system may actually cover 81% of the ECTS of the bachelor degree in Chemical Engineering and Biotechnology taught at Aalborg University, which emphasizes project organized problem based learning. This large degree of coverage, exemplified for both classroom topics and student projects leads, to the conclusion that brewing may be regarded as a comprehensive learning platform in chemical engineering.



KEYWORDS: *First-Year Undergraduate/General, Second-Year Undergraduate, Upper-Division Undergraduate, Chemical Engineering, Hands-on Learning, Applications of Chemistry, Consumer Chemistry*

■ INTRODUCTION

Chemical engineering is in many ways a craft that can only truly be learned through hands on experience. However, economic considerations or safety issues may prevent institutions from acquiring equipment that students can use for pilot scale investigations, and instead, the students may have to study the processes in small test tubes or through computer models and simulations. Because the span of fields where chemical engineers can find work is so great, it may also be difficult for the respective institutions to find and invest in relevant equipment that can cover all aspects of the education. One process that potentially can cover most aspects of traditional chemical engineering, and which is safe for students to work with, is beer brewing.

Over the years, brewing has been brought to the lab and classroom as a teaching tool or as a case study to illustrate and enhance concepts[1−5] and experimental work related to beer has also been published on some occasions in educational journals.[6−10] Some main activities include beer as a class topic to place chemical concepts from basic courses, such as pH, solubility, reactions, equilibrium and fermentation, into a larger context.[2] This study showed that using beer as a basis functioned very well in aiding students in systematize and elaborating on concepts as well as emphasizing the importance of chemistry. Another activity was using the fermentation of beer to help illustrate and facilitate understanding of metabolic processes in undergraduate biochemistry courses.[5] On the basis of this study it was concluded that the incorporation of fermentation of beer helped create a classroom-lab link as well as increase laboratory skills.

This paper aims to provide an overview of why brewing may be used as a learning tool, or even a learning platform, in chemical engineering, providing both classroom-laboratory links, utilization of different concepts within chemistry, biochemistry, and engineering as well as an understanding of the transition from laboratory experiments to larger scales such as pilot scale operation. The term learning platform is used to emphasize that it is not just a few single subjects in chemical engineering that may be related to brewing, but in reality, a large part of the topics and courses in a bachelor degree may be exemplified through brewing.

Brewing Process

During brewing, malted barley or another starch containing compound is heated to convert starch into fermentable sugars through enzymatic reactions with α- and β-amylases. This process, termed mashing, produces primarily glucose, maltose, and maltotriose as well as some dextrins. Subsequently, the mash is separated into a liquid (wort) and a solid part during lautering, which traditionally is a dead-end filtration process. Following lautering, the wort is boiled with hops to add the characteristic flavor as well as killing unwanted bacteria that may be present in the wort after lautering. During wort boiling,

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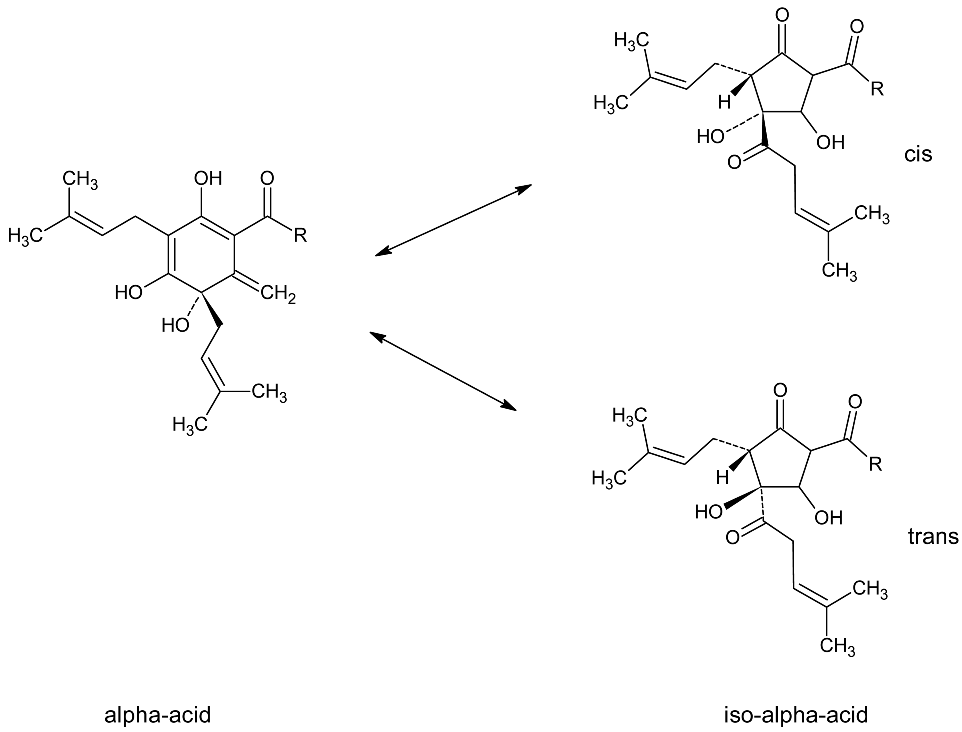

Figure 1. Isomerization of α-acid, R denotes $-CH_2CH-(CH_3)_2$ (humulone), $-CH(CH_3)CH_2CH_3$ (adhumulone), or $-CH(CH_3)_2$ (cohumulone).

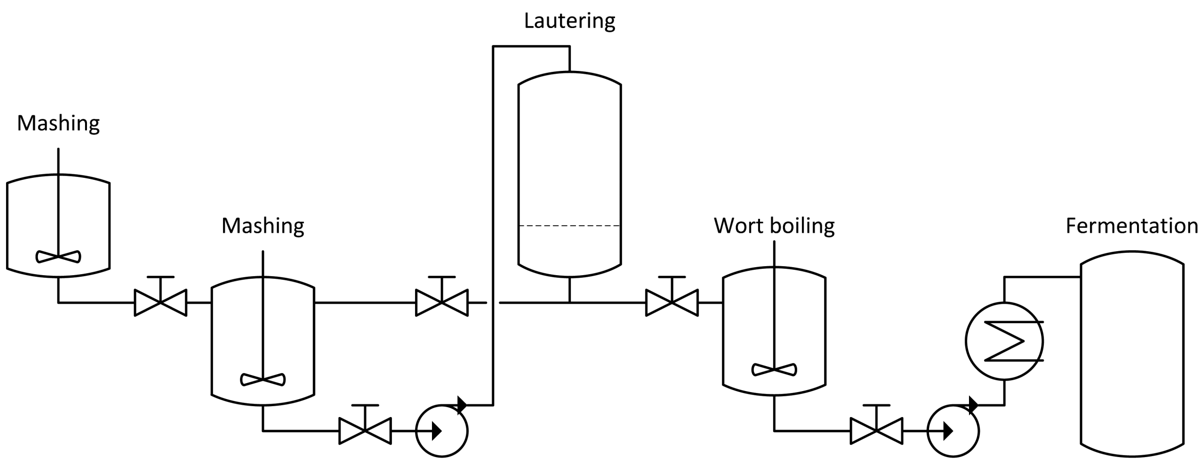

Figure 2. Principle of the pilot scale brewing system such as employed at Aalborg University, Esbjerg Campus.

the α-acid in hops is isomerized to iso-α-acids, cf. Figure 1, adding to the bitterness of the beer.

The wort is cooled and yeast added to start the final stage of the process, the fermentation. During fermentation the yeast consumes the fermentable sugars and produces ethanol.

Figure 2 illustrates the pilot scale setup used for brewing at Aalborg University, Esbjerg Campus.

The two mash tuns as well as the wort boiling tun are steam heated. The vessels are all connected to a cold water supply, so hot water is either generated in the upper mashing tun or the entire mixture of water and malt heated using the steam heating mantles on the vessels. Because of the size of the system, malt is added manually to the tuns through openings in the top.

The pilot scale setup has the option of working with two mash tuns, allowing for more versatility in the mashing step. Mashing could be done in just a single mash tun (normally the lower tun), or an infusion mashing could be performed by adding hot water/liqour from the upper tun. However, it would also be fully possible to conduct two mashings simultaneously. The upper tun has also been used in connection with mashing of nonmalted stach sources, where the upper tun was used for these, whereas the malt was mashed in the lower tun.

All vessels where heating occur are stirred with an impeller at the bottom of the vessel. Because the vessels are heated on the bottom using steam, having the impellers at the bottom reduces the risk of malt depositing on the surface directly heated by the steam. Furthermore, the impellers also may be used to study the effect of stirring on the temperature gradients of the vessels.

Learning Aspects in Brewing

The brewing process has a lot of possibilities to be used as a learning platform in chemical engineering education, especially when working with pilot scale operation (50−100 L), but also in a lab scale environment. A multitude of topics in fundamental organic and inorganic chemistry may be

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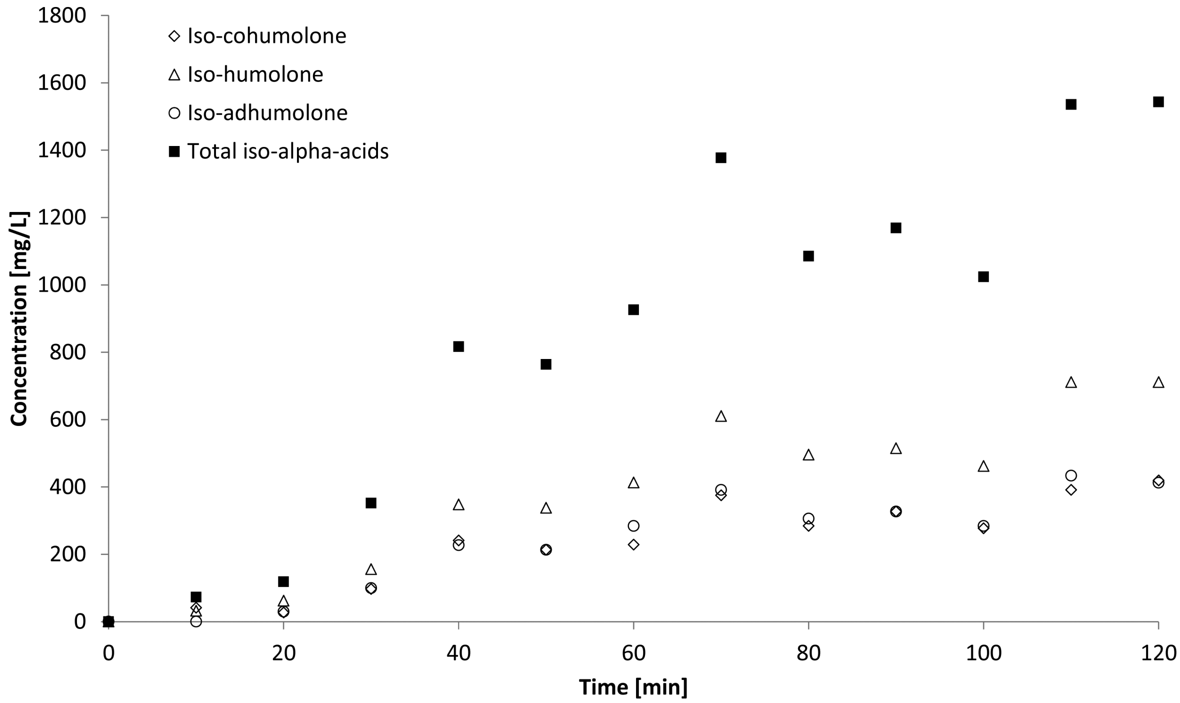

Figure 3. Isomerization of α-acids in Saaz hops over time during wort boiling.

exemplified through brewing; this may be pH, solubilities, reactivity, equilibria, and isomerization, and in reality, a large part of the topics and courses in a bachelor's degree, and to some extent a master's degree, may be exemplified through brewing.

It is important to note that when describing the learning aspects, it is not necessarily that experimental work is conducted on a full brew. A key part to this is extracting or isolating a process or reaction within the brewing process and reproducing this in a laboratory setting. This not only allows the students to investigate details of the overall process in a more controlled environment than a pilot scale setup but now and then also shows discrepancies between laboratory results and actual brewing results. This provides an important lesson regarding scaleup of processes and that everything that may be achieved in a simplified and very controlled lab experiment may not necessarily yield the same result in an actual brewing process.

The following sections describe how various topics in the chemical engineering education may be related to brewing with some examples of student work in the fields. The Supporting Information supplied with this paper details some aspects of how to conduct these and other relevant experiments to give a starting point with introducing brewing into chemical engineering education and are based on the facilities available at Aalborg University Esbjerg Campus so adaption to other facilities may be required.

Analytical Chemistry. Instrumental analytical chemistry is relevant in all stages of the brewing process to measure contents of fermentable sugars, ethanol, α-acids, and so forth to both evaluate the process as well as generating data on which to base any process models. With regards to analysis most would be relevant for HPLC analysis may be used for measurements of fermentable sugars, ethanol, α-acids and could be considered one of the main analytical methods in relation to brewing. However, concentrations of minerals in the beer and the utilized water could be determined using atomic absorption spectroscopy (AAS) or inductively coupled plasma atomic emission spectroscopy (ICP-AES).[11] This would be relevant because the mineral content of water used for brewing does affect the brew process and the final product.[12−14] Not only are minerals relevant to measure because trace amounts of metals such as tin and iron also may account for haze in the beer, which is also an unwanted effect.[15] Also, spectroscopic methods, such as near-infrared (NIR) or Raman spectroscopy may be used in relation to brewing. Examples of these applications are α/β-acid determination as well as yeast concentration using NIR, whereas infrared and Raman spectroscopy has been applied for process monitoring during mashing and wort boiling.[16] Using vibrational spectroscopy for monitoring allows for online process monitoring in a nonintrusive way, which may resolve some of the issues that can normally be associated with sensors placed in a process module, such as hard to clean spaces.

An example of this is the analysis of α-acids in hops and to which extent they are isomerized during wort boiling. This work was done using HPLC methods to monitor iso-α-acid contents during wort boiling, starting with method development using lab scale test and subsequently showing the applicability in a larger scale production. This could be used to monitor how well the hops added to the wort are fully utilized in adding bitterness to the beer.

The project managed to determine the isomerization of α-acids in a Saaz hops during wort boiling, yielding results as shown in Figure 3, which show the results of the initial lab work. As seen here, laboratory tests in demineralized water using a large amount (600 mg/L) of hops yielded concentrations higher than those observed in regular brews. These results should then subsequently be related to the actual brewing process, the time of adding the hops to the wort and the optimal time of boiling being determined from these initial lab experiments.

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Colloid and Interface Chemistry. Likewise, in colloid and interface chemistry, beer does pose as a good candidate for linking classroom and laboratory experiments. The chemistry of beer can be used to introduce important colloid and interface areas as stability of colloids, foams, electric double layer, particle size, zeta potential, turbidity, surface tension, adsorption, sedimentation, and viscosity.[1] Colloid and interface science is of particulate interest when focusing on the stability of beer during its shelf life. Filtered beer can be regarded as a water—ethanol mixture with different dissolved components in which colloids (e.g., proteins) are dispersed. Chill haze is one of the first signs of colloidal instability in a beer, which is a reversible interaction between low polymerized polyphenols (tannoids) and proteins. The tendency to form chill haze increases over time. Polymerization of the polyphenols results in a stronger bonding to the proteins and hence a permanent haze.[17] The haze formation may be investigated using optical and light scattering techniques, that is, turbidity and particle size measurements. Stabilization of the beer is ensured by controlling the haze forming protein and polyphenol content.

The colloidal stability of the beer can be optimized by carefully selecting the raw materials and process strategies. Additionally, removal of the haze precursors (polymerized polyphenols and proteins) can be achieved by adsorption using, that is, polyvinylpolypyrrolidone (PVPP) and silica gel followed by filtration.[17,18] This introduces the charges and stability of particles.

Another example is the head or foam generated when pouring a beer. Foams are a two-phase system of gas (CO_2) and liquid forming a network of gas bubbles trapped in thin liquid films. The beer foam is stabilized by adsorption of hydrophobic proteins and polypeptides at the gas/liquid interface. The ethanol present in beer helps the formation of foam by lowering the surface tension resulting in creation of smaller gas bubbles.

Biochemistry and Microbiology. The fermentation part of the process is an excellent platform for teaching in microbiology as the output is highly influenced by several microbial processes. The most important microbial process in beer making is of course the conversion of sugars to alcohol by yeast. The first pure culture yeast strain for beer making, *Saccharomyces carlsbergensis*, was isolated in 1883 by the Danish mycologist Emil Christian Hansen working at Carlsberg.[19] Since then, most beers rely on fermentation by wide variety of pure yeast cultures primarily belonging to the *Saccharomyces* complex with *S. cerevisiae* as the predominant species. The different strains have different temperature optima, alcohol tolerance, and ester production that are used by breweries to differentiate beer tastes and alcohol content. The strain variation can be used for teaching purposes in molecular biotechnology courses, through phylogenetic analyses, where selected genomic regions are amplified by polymerase chain reaction, sequenced, and aligned.[20] The available genome sequences[21,22] can also be used to examine the transcriptome and proteome during fermentation processes.

The cereals used to brew beers can be contaminated with mycotoxins, which are harmful secondary metabolites produced by filamentous fungi either during infection of cereals growing in the fields or during storage. Some of these mycotoxins are degraded or transformed during the brewing processes or fermentation, whereas others pass through to the final beer product.[23] The fate of the individual mycotoxins can be monitored in analytic chemistry courses by high performance liquid chromatography coupled to UV detection or mass spectrometry.[24]

A phenomenon termed gushing, where the beer vigorously over foams immediately on opening, can occur in beers with are produced from cereals infected with filamentous fungi. Gushing is caused by the contamination of fungal hydrophobins[25] and the chemical processes involved can be examined in chemistry courses.

Another example was a group of students investigating the utilization of carbohydrates (maltotriose, maltose, and glucose) by different yeast strains and the resulting production of ethanol over time. This project led the students to use analytical techniques such as HPLC for concentration measurements and helped them gain a further understanding of the anaerobic fermentation. Figure 4 shows some of these results plotted, showing how ethanol production is significantly delayed in one strain (US-05) compared to two other strains (WB-06 and S-04).

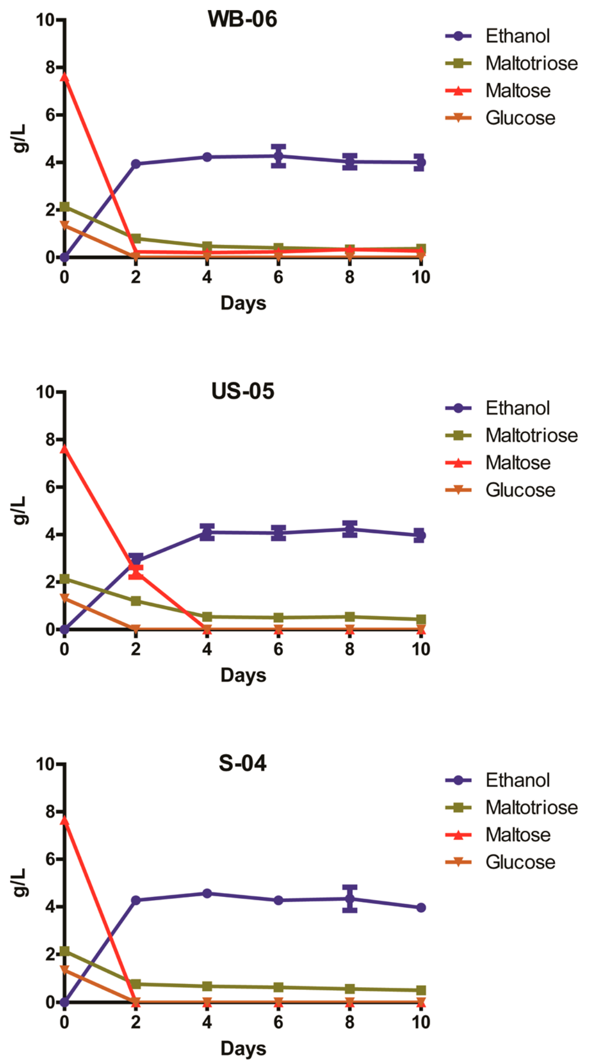

Figure 4. Changes in concentration of ethanol, maltotriose, maltose, and glucose (g/L) during 10 days fermentation of three different yeast strains (WB-06, US-05, and S-04) in malt extract medium. Three independent samples were analyzed at each time point for each strains and the data is shown as mean values with error bars representing standard deviation.

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Table 1. Course Modules and Semester Themes for a B.Sc. in Chemical Engineering at Aalborg University

Semester	Course Modules	Project Themes
1	Problem Based Learning in Science, Technology and Society	Chemical and Bioindustrial Products[a]
	Organic Chemistry[a]	
	Linear Algebra	
2	Bioactive Molecules—an Introduction to Biological, Physiology and Toxicology[a]	Chemical Reactions in Natural and Technical Systems[a]
	Introduction to Chemical Engineering Thermodynamics[a]	
	Calculus	
3	Methods in Qualitative Chemical Analysis[a]	Analysis of Chemical Systems[a]
	Inorganic and Physical Chemistry[a]	
	Applied Statistics	
4	Chemical Thermodynamics and Separation Process Engineering[a]	Material Science/Applied Microbiology[a]/ Petrochemical Separation Processes
	Biological Chemistry[a]	
	Material Science and Material Selection[a]	
5	Chemical Reaction Engineering[a]	Chemical Process Engineering[a]/ Bioprocess Engineering[a]/ Refinery Products and Processes
	Fundamental Fluid Mechanics and Heat Transfer[a]	
	Mathematical Modeling and Numerical Methods	
6	Design of Experiments	B.Sc. Thesis[a]
	Process Control, Instrumentation and Safety[a]	
	Theory of Science and Entrepreneurship	

[a]These items are assessed as a course or project that may be related to brewing.

Process Technology and Design. When brewing on pilot plant scale, it is relevant to considers aspects of process engineering such as reactors, heat exchangers, filters, pumps, valves, and so forth. Linking this scale of process to classroom educations in unit operations and process engineering allows for students to observe/experience theoretical aspects on a first hand basis. This could be heat exchangers where calculations of required size or flow may be done theoretically, but the operation of actual heat exchangers allows for verification of calculations with experimental data and effects such as fouling also may be observed. Also, larger scale vessels mean that gradients in temperature may be observed. This makes it relevant to consider elements of stirring and how to maintain even concentrations in larger volumes, something that a beaker in a laboratory cannot show. This is where computational aspects such as CFD may be used to generate models of gradients and mixing in the vessels and to evaluate if assumptions of uniform concentrations in reactors may be appropriate. Furthermore, the possibilities of including transport processes as well as mass and energy balances are extensive. With heating cooling and several inputs/outputs to the process the system provides a good basis for mass and energy balances, whereas transport processes, especially heat transfer, is a key aspect in all steps of the process.

Furthermore, fluid flow topics, such as fluid mechanics, pressure drops in pipelines, and valves as well as pump characteristics and operation are excellent topics to cover using a pilot scale system. These topics are relevant in any type of chemical processing and gives a possibility for a hands-on experience with these central topics.

Because reactions are taking place in the vessels for mashing and wort boiling, these can be regarded as reactors, thus implementing courses in chemical reaction engineering. In this respect, the vessels may be batch reactors, but from experimenting with these processes, the student can derive kinetic data and gain a fundamental understanding of reactor design as well as considering the topic of mass transfer in reactors as well.

Also, the understanding of process design, placement of sensors and how to create control systems and document these are all relevant skills that are trained when using the larger scale equipment because a significant amount of control and monitoring needs to be implemented to have a semi-automated or fully automated brewing facility.

An example of this is students studying heat gradients in the wort boiling and mashing vessels. This was done by making a three-dimensional grid of thermocouples within the vessels and monitoring temperature throughout the vessel during brewing. This could be used to evaluate if the reactions during mashing could be expected to proceed at a uniform pace which could impact the amount of fermentable sugars later in the process in case of nonuniform temperatures. A procedure for this is found in the Supporting Information.

Encompassing a Bachelor Degree in Chemical Engineering in the Beer Platform

To illustrate how brewing may be used as a comprehensive learning platform in chemical engineering, the current curriculum for the bachelor degree in Chemical Engineering and Biotechnology at Aalborg University is assessed to determine how large a part of this could be related to brewing.

Aalborg University uses project-organized problem-based learning (POPBL)[26] system, where students conduct group-based project work relating to a problem that needs to be solved each semester. Every semester has the structure of three courses each of 5 ECTS and one project of 15 ECTS (in the first semester, however, this is divided into a 5 ECTS introductory project and a 10 ECTS project). In some semesters, there may be the possibility of choosing between several project topics, but courses are always fixed.

Table 1 lists the course modules and project themes of the semesters of the B.Sc. program, and as it may be seen, the project themes would all allow for projects relating to brewing in one way or the other.

Examples of projects that have been conducted relating to brewing are investigations of fermentation, process modeling of

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mashing, increasing efficiency of lautering and analysis of hops, all done with lab scale and pilot scale experiments.

With regards to courses, then 55 of the total 90 ECTS (61%) worth of courses may be related in one way or another to brewing. The courses that may not be linked to brewing are the courses that provide tools, such as calculus, statistics, and design of experiments, that are prerequisites for other courses and to plan and evalutate experimental runs and the gained data as well as establishing mathematical models describing real world systems.

Summing this up would leads to that 81% (100% of the project ECTS and 61% of the course ECTS) of the B.Sc. curriculum in chemical engineering may be directly related to and exemplified by brewing. Furthermore, taking into account that some of the courses not directly related are courses that provide tools for the trade, then it may be reasonable to claim that brewing may be used as a comprehensive learning platform for chemical engineering. As a result, for institutions involved in chemical engineering education with limited space or financial capacity, investment in a brewing pilot plant could as such be a way to still allow students access to large scale process equipment.

The degree of implementation of brewing as a learning platform is of course up to the course responsibles, this just illustrates that the possibility is there and that there may be merit in doing so. Especially in projects there are a lot of possibilities for brewing related learning. Because of the nature of POPBL, students are encouraged to design their own experiments and develop their own hypothesis for their investigations. Normally, students start out analyzing the process and extracting some part of the process to investigate in further detail. This is then initially investigated in the lab where students analyze detailed aspects which are later on related to an actual brew. This means that students go through several steps to help their leaning including analysis of the process, development of hypothesis, testing in lab scale, and finally, relating lab scale to pilot scale and evaluating if the developed lab scale experiment is representative of the larger process. That students go through these steps with the guidance of a supervisor teaches them a series of important scientific aspects. The function of the supervisor or instructor is to facilitate the students learning, but not giving them specific tasks to solve. This means that sometimes students develop experiments that are not fully descriptive or oversimplified, but the supervisor will then through discussion point them toward a more suitable direction. This means that learning in this POPBL context has a lot of freedom for the students to choose their focus and direction of the project work but at the same time promotes the feeling of ownership of the project due to it being directed by the students and not a task set by a supervisor.

■ CONCLUSION

Beer has always been of interest to students, and it has on several occasions been shown that brewing may be used to generate good classroom-laboratory links and engage the students. It is in this work argued that brewing is not only relevant for a few fundamental courses, but may actually be viewed as a comprehensive learning platform in chemical engineering education, providing relevant classroom-laboratory links and possibilities for a significant number of central topics in chemical engineering, such as process engineering and control, microbiology, and general chemistry as well as analytical aspects. This is illustrated in Figure 5, how topics in brewing may fit within one or more educational areas.

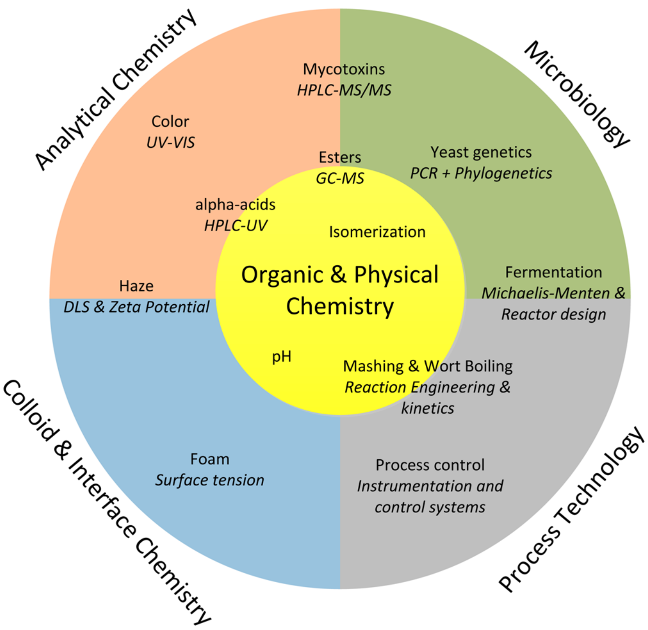

Figure 5. Examples of topics in brewing and their relation to educational areas.

As an example the B.Sc. curriculum in Chemical Engineering and Biotechnology at Aalborg University has been used to see how many of the courses and projects potentially could be related to brewing. In total, 11 out of 18 courses and all project modules could be related to brewing in one way or another, meaning that brewing in this case could be more than just a small detail but rather a learning platform for the engineering education.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.5b00994.

A series of experiments that may be used in teaching chemical engineering aspects in brewing. A total of five experiments are proposed relating to yeast strains, hops and wort boiling, temperature gradients, and heat exchangers. (PDF)

A series of experiments that may be used in teaching chemical engineering aspects in brewing. A total of five experiments are proposed relating to yeast strains, hops and wort boiling, temperature gradients, and heat exchangers. (DOCX)

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Notes

The authors declare no competing financial interest.

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