JOURNAL OF CHEMICAL EDUCATION

pubs.acs.org/jchemeduc Article

Food Fermentations and Flavor: A Curiosity and Creativity Driven Approach for Interdisciplinary and Research-Oriented Science Education

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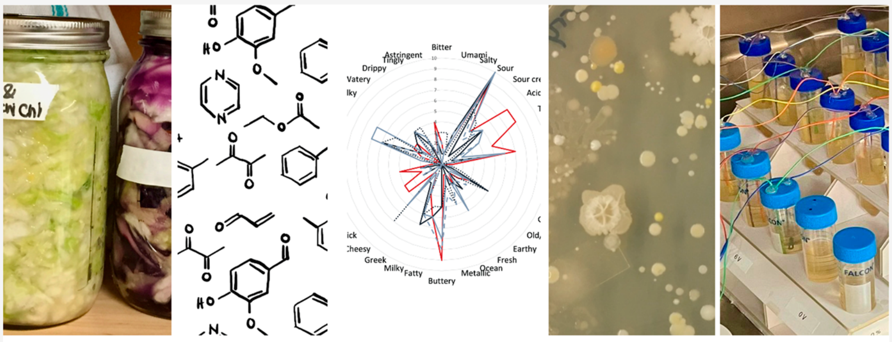
Cite This: *J. Chem. Educ.* 2023, 100, 2935−2946 Read Online



ABSTRACT: The interdisciplinary nature of food makes it an effective teaching vehicle in many fields. This article shows specifically how flavor and food fermentation, two topics not usually featured in the undergraduate STEM curriculum, can inspire a powerful interdisciplinary learning experience. Importantly, because of their accessible nature and relatively unexplored status in current research, these two topics are also uniquely attractive as authentic research experiences for students from diverse backgrounds. Focusing on these topics, the author designed and executed a student-centered science course. The course is unusual from other Course-based Undergraduate Research Experiences (CUREs) in being highly inquiry-driven and discovery-based, with students independently defining their research topics. By emphasizing curiosity, creativity, and practicing how to generate "good" research questions, the course fills a gap in the traditional undergraduate research experience and curriculum. The findings of the article are based on hundreds of enrolled students from five course offerings. It shows that the course promotes student engagement and curiosity, as well as gains in conceptual learning and in self-reported learning of concepts and science skills. Further, students report valuing the hands-on and inquiry-based format for improving their learning, engagement, and sense of curiosity about the material.

KEYWORDS: *Undergraduate, interdisciplinary, inquiry-based/discovery learning, fermentation, flavor, curiosity, creativity, gas chromatography, mass spectrometry, sensory analysis, undergraduate research*

1. INTRODUCTION

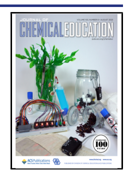
National guidelines increasingly call on universities to promote interdisciplinarity, inquiry-based learning, and authentic research experiences in undergraduate STEM education.[1−6] All three of these aims have important related goals, such as increasing learning, engagement, and persistence in STEM fields, mirroring how scientists work, and promoting scientific literacy and critical thinking.[7−9]

The work described in this article shows how food fermentations and flavor can be engaging subjects for inquiry-based interdisciplinary science teaching. It also shows that they can provide a rich source of topics for authentic, discovery-based research experiences for undergraduates. The author proposes that learning experiences, such as the type of course that was developed to achieve these aims and goals, can play an important role in the undergraduate curriculum, especially by fostering creativity and curiosity in an education system that increasingly emphasizes early specialization and test preparation.

1.1. Food Fermentations and Flavor for Integrated Chemistry and Biology Education

The interdisciplinary nature of food makes it an effective teaching vehicle for many fields. It has successfully been used to

Received: November 25, 2022
Revised: July 2, 2023
Published: July 20, 2023



https://doi.org/10.1021/acs.jchemed.2c01153
J. Chem. Educ. 2023, 100, 2935−2946

teach concepts in chemistry,[10,11] physics,[12,13] biology[14,15] and engineering.[16−18] It allows for engaging connections between the sciences, humanities and social sciences.[19] Its inclusive and accessible nature—it is part of everyone's life and is culturally and geographically diverse—makes it a powerful subject for general education courses for nonscience majors, and outreach programs for K-12 and the general public.[19−22] In addition, cooking is hands-on, experimental, and creative, lending itself well to teaching experimental practices and scientific inquiry. Laboratory exercises featuring food and cooking can be performed with sustainable materials, and can be adapted for at-home experiments in students' kitchens.[23−27]

The engaging nature of food as a teaching tool is often explained by its tactile, visual, and delicious properties. Yet, even in recent years, as food related pedagogy has become more common, flavor, one of its key attributes, plays a limited role in most curricula. This is a noteworthy omission: Human beings rely on only five senses to interpret the world around us. Flavor draws on at least two of them, taste and smell, and one of these, smell, is often considered to be the sense that is the least well understood.[28−30] Flavor is produced in food in a limited number of ways: (1) by being inherently present in cooking ingredients, (2) by chemical breakdown of larger molecules with heat or over time, such as with Maillard reactions or aging, or (3) by microbes in food fermentations, the latter being the subject of this study.

As a culinary practice, cooking with microbes is ubiquitous, culturally diverse, and has a rich and long history.[31−33] Fermentation has traditionally been used for food preservation and creation of intoxicants and flavorful ingredients. In recent decades, haute cuisine chefs have increasingly embraced it as a tool to create novel flavors, limit food waste, and experiment with unusual ingredients.[34−36] The trend is mirrored in the science community where food fermentations have gained traction as a tool for understanding microbial communities.[37,38] The general public is also enthusiastically engaging with home-fermentations, with online forums and festivals abounding.

1.2. Open-Inquiry Teaching Leading to Authentic, Curiosity-Driven Research Experiences for Undergraduates

The benefits of inquiry-based learning are well-documented.[39−42] The term is broad and ranges from highly structured, to only partly guided, to very open formats. All models have in common that they avoid directly lecturing students about the answers to questions and instead involve them in asking questions that lead to the answers. At the far end of the spectrum are curricula that allow for very open questions with large flexibility in answers; these curricula can be designed to mimic the authentic inquiry process of professional researchers.

Similar to inquiry-based learning, the benefits of student research experiences are also well documented.[43−45] Within a curriculum, the term "authentic research" can mean many things. It often refers to experiences where neither students nor instructors know the outcome, but the emphasis on different components of the research process can vary. It usually involves various aspects of the ordinary process of advanced research itself, such as experimental design, data analysis, and scientific communication, as well as the generation of novel results and publishable data.[7,8,43] Research experiences that emphasize creativity, curiosity, and the ability independently to generate "good" research questions are less common, but these are all critical skills for practicing scientists and any future alum confronting the current challenges facing humanity.[46,47]

These aspects of the research process can be challenging to incorporate into the undergraduate curriculum. For example, the research conducted in most faculty laboratories requires deep familiarity with a field, making it challenging for an apprenticing student to contribute in meaningful ways by engaging their curiosity, asking their own questions, and exploring creative ways of answering them. Similarly, many research focused courses, including many Course-based Undergraduate Research Experiences (CUREs), involve the instructor or some outside entity defining all or some part of the question or helping in analysis of the results.[43,48,49] On the other side of the spectrum are courses that, although fostering creativity, may involve student research that is elementary or disconnected from current research in a field, or lack a hands-on component, such as might be the case in introductory courses or literature-based investigations.

In this article, the author proposes an inquiry-based curriculum that avoids these extremes and manages to promote creativity, curiosity, and the value of asking questions as a way for students to delve deeper into the material, ultimately defining a research question. The topics of flavor and fermentation are well suited for this type of authentic research experience for the following reasons: (1) Neither topic is typically covered in depth in the traditional STEM curriculum, providing students from different scientific disciplines with a common starting point. Minor exceptions occur in health/GOB curricula.[50] (2) Both topics are broad and interdisciplinary enough to provide access points for discovery-based research for students from diverse academic backgrounds. Student majors ranging from engineering to chemistry to biology can contribute in meaningful ways by applying skills and knowledge in novel contexts. This creates opportunities for students to develop skills in interdisciplinary team-work. (3) Flavor and fermentation have the additional benefits of being sufficiently accessible for a relative novice, while also being relatively unexplored compared to many scientific fields, allowing for undergraduates to engage in an authentic discovery-based process that explores current questions in a field.

2. RESULTS AND DISCUSSION

2.1. Course Design and Content

The author designed and executed a science course for undergraduates that applies the topics of food fermentations and flavor for integrated teaching of concepts in chemistry and biology. The course is student-centered, hands-on, and taught in a curiosity-driven, open-inquiry style that mixes hands-on exercises, readings, short lectures, visiting speakers, and field trips. In the second half of the course, students engage in a multiweek research experience in small teams. Prerequisites include one semester of college level biology and general chemistry or equivalent; organic chemistry is recommended. Using this format, several hundred students have taken this course in a small seminar format. The study described in this article reports on the results from five of the eight years of the course's offerings.

The novelty of the course is 2-fold. First, curiosity and "asking questions" are the driving mechanisms by which students delve deeper into the material, ultimately leading to a research project. Second, the course brings together two different areas of science: flavor and fermentation. The first topic, flavor, plays a central

Table 1. Content Summary for the Four Course Blocks Including Science Topics, Class Exercises, Assignments, and Examples of Past Visiting Speakers and Field Trips[a]

COURSE BLOCK	TOPICS	EXERCISES	ASSIGNMENTS	VISITING SPEAKERS	FIELD TRIPS
1. FERMENTED FOODS	Fermentation practices, underlying science, history, cultures	Hands-on fermentations	Asking and engaging with individual questions and as a class, student presentations, class-wide projects, experimental design, analysis and interpretation of results, team-work	Practitioners and restaurant R&D: Sandor Katz, Noma Fermentation Lab, Mugaritz Restaurant, Nordic Food Lab, Basque Culinary Center	Companies: chocolate maker, brewery, cheese shop/cave, synthetic biology companies s.a. Gingko Bioworks
2. FLAVOR	Physiology	Taste exercises		Flavor specialist	Tufts University Sensory and Science Center
	Sensory analysis	Sensory panel		Sensory scientist	
	Multisensory flavor perception	Multisensory exercise (compose music)		Multisensory music instructor/composer	
3. MOLECULES	Properties and characterization of flavor molecules and metabolites, GC/LC-MS	Gas and liquid chromatography, mass spectrometry		Mass spectrometry specialist	Harvard Small Molecule Mass Spectrometry Facility
4. MICROBES	Exponential growth, successions & communities, metabolites and biochemical pathways, characterization	Microscopy, plating, sequencing		Sequencing specialist, academic fermentation researcher	Harvard Bauer Core sequencing facility

[a]The schematic shows reproducible content across all offerings. Visiting speakers and field trips vary by year; a typical course offering may feature 2–3 field trips and 3–5 visiting speakers.

role in the way humans sense the world, yet many aspects of this field are poorly understood. The topic has attracted interest from diverse fields ranging from chemistry, physics, and neuroscience to psychology, history, and sociology.[28−30,51] The second topic, fermentation, offers a powerful tool for addressing current questions in science and society.[52,53] The microorganisms involved produce an array of specialized small molecules as part of their metabolic processes. The course studies the chemical and biological aspects of their production, properties, and characterization through the lens of food fermentations. In particular, the course focuses on the small molecules that contribute taste and aroma in fermented foods.[54] Isolated fermented food products have previously been used to teach sequencing (sourdough)[15] or other microbiological or chemical techniques as part of modules in larger classes (kefir, yogurt, kombucha, brewing),[14,55,18,56,57] but fermentation as a whole, on its own and as it relates to flavor, is only rarely reported in learning contexts.[58] One exception is the online version of the course described in this article, which was launched seven years after the inception of the original, residential course, and has a different curriculum and pedagogy.[59]

Together, the two fields of flavor and fermentation cover topics in chemistry, microbiology, biochemistry, engineering, flavor science, sensory sciences, psychology, and data analysis and statistics. It is rare that these subjects come together in a curricular setting.

2.2. Course Design: Concepts

The course content is divided into four main blocks, each roughly a few weeks long (Table 1 and a representative syllabus is available in the Supporting Information). Each block overlaps to some degree with the others, such that the topics sometimes appear in parallel and inform each other.

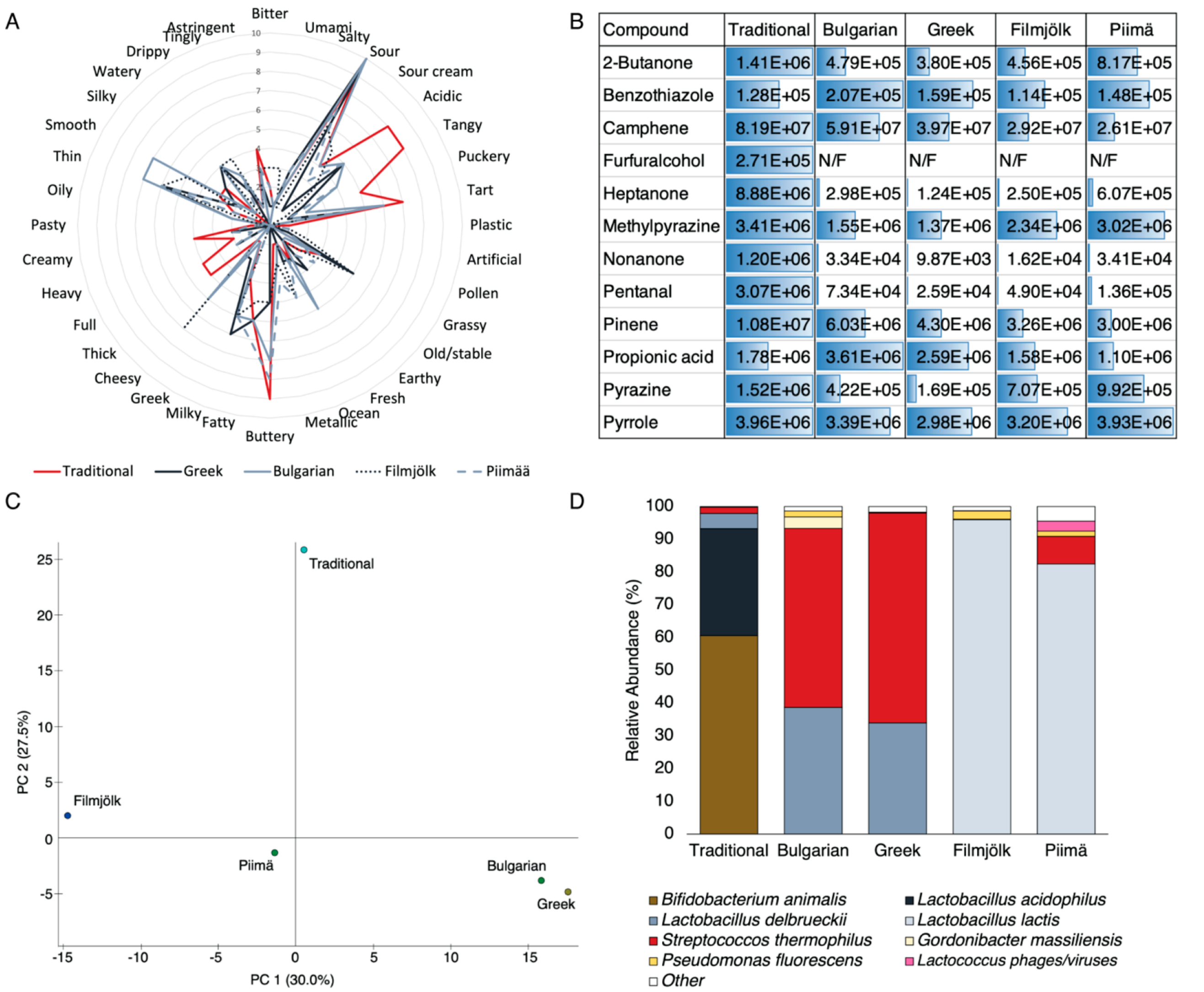
2.2.1. Block 1: Fermented Foods—Practice, Science, Culture, History. The first block introduces fermented foods in terms of the practice, science, culture, and history. It begins with the two most prevalent types of food fermentations: alcoholic fermentations with yeast and lactic acid fermentations with lactic acid bacteria (LAB). Without too much emphasis on theory, students engage in hands-on exercises as early as the first or second class meeting: bread and mead for yeast fermentations; sauerkraut, pickles, and yogurt for LAB fermentations. Since fermentation takes time, these ongoing fermentations carry through to the other blocks of the course. For each exercise, the class as a whole performs a variety of modifications with each student doing a subset. For example, sauerkraut with different spices and ingredients or bread with many different yeast and flour varieties. Students collect data from their fermentations on the board or a shared sheet and analyze and discuss it in person and in an online discussion forum. Examples of measurements include the pH, specific gravity, gas volume, color, and flavor. They also engage in community building show-tell-and-taste exercises, which give students the opportunity to share ideas and build trust and community. A list of laboratory equipment and materials, instructions for the hands-on fermentation exercises, and assignments are available in the Supporting Information.

Block 1 also features the first steps of a multiweek classwide experiment, which is followed in greater detail in Blocks 2–4. Figure 1 shows the results of one such exercise, for which the class prepared yogurts with different microbial cultures.

Having covered the two most common types of food fermentations, the curriculum progresses to mixed-culture fermentations (sourdough, beer, and kombucha). This allows for exploration of complex microbial interactions and communities. From here, the curriculum moves to mold fermentations (koji, miso, soy sauce, amazake, and tempeh). After this follow meat and fish fermentations, which are noteworthy because the primary substrates are proteins and fats as opposed to carbohydrates. Finally, the block concludes with cheese, coffee, and chocolate fermentations, all being complex, and usually endogenous, ecological successions.[60−62] In parallel with the aforementioned topics, students are exposed to a wide variety of fermentation practices through individual student explorations, where students learn about a topic on their own and present it to the class. This exercise is one of the ways in which the curriculum allows each student to tune their course experience to their individual knowledge level and interest.

Overall, the first block of the course demonstrates the basic science underlying food fermentations, the ubiquity of fermented foods in every-day life, as well as the diverse cultures

https://doi.org/10.1021/acs.jchemed.2c01153
J. Chem. Educ. 2023, 100, 2935−2946



Compound	Traditional	Bulgarian	Greek	Filmjölk	Piimä
2-Butanone	1.41E+06	4.79E+05	3.80E+05	4.56E+05	8.17E+05
Benzothiazole	1.28E+05	2.07E+05	1.59E+05	1.14E+05	1.48E+05
Camphene	8.19E+07	5.91E+07	3.97E+07	2.92E+07	2.61E+07
Furfuralcohol	2.71E+05	N/F	N/F	N/F	N/F
Heptanone	8.88E+06	2.98E+05	1.24E+05	2.50E+05	6.07E+05
Methylpyrazine	3.41E+06	1.55E+06	1.37E+06	2.34E+06	3.02E+06
Nonanone	1.20E+06	3.34E+04	9.87E+03	1.62E+04	3.41E+04
Pentanal	3.07E+06	7.34E+04	2.59E+04	4.90E+04	1.36E+05
Pinene	1.08E+07	6.03E+06	4.30E+06	3.26E+06	3.00E+06
Propionic acid	1.78E+06	3.61E+06	2.59E+06	1.58E+06	1.10E+06
Pyrazine	1.52E+06	4.22E+05	1.69E+05	7.07E+05	9.92E+05
Pyrrole	3.96E+06	3.39E+06	2.98E+06	3.20E+06	3.93E+06

Figure 1. Example of a class-wide project from one year's course offering with the theme "yogurt". Dairy fermentations, such as yogurt, occur in diverse cultures around the world. The key microbes are a variety of lactic acid bacteria, all having in common that they convert lactose in the milk to lactic acid. The acidic pH prevents growth of spoilage microbes, thickens the texture, and imparts a sour flavor. Depending on the microbial community composition, the resulting yogurts range from thick to thin, stringy to lumpy, and with flavor profiles of fruity, buttery, or cheesy.[60,64,65] The limited number of ingredients, only milk and microbes, in combination with the straightforward preparation technique—temperature and fermentation time are the only experimental variables—make dairy fermentations effective experimental systems. The main substrate, milk, is a homogeneous material, i.e., as long as the time, temperature, and type of milk are kept constant, any variation in flavor and texture can be directly attributed to differences in the microbial cultures. Like all of the class-wide projects, the yogurt project occurred over multiple weeks and stretched across all four blocks of the course. Students prepared five different yogurts in Block 1, and analyzed their flavor profiles with sensory analysis in Block 2 (A). In Block 3, they analyzed the volatile aroma compounds with GC-MS (B) and metabolites with LC-MS (organized into a Principal Component Analysis plot showing similarities between yogurts in C). Finally in Block 4, they characterized the microbial communities with Next-Gen sequencing (D).

and geographies in which they occur.[63] Since food fermentations have a millennia-old history in human culture, this block also discusses historical evidence for the earliest known food fermentations. In addition, visiting speakers and field trips highlight how professional experts approach food fermentations for optimal results.

Through the hands-on exercises, the following types of questions are explored: What can the fermentation recipes and our observations tell us about the underlying science? Can the science help us predict and manipulate the outcomes, such as the final alcohol content in mead and the degree of leavening in bread? What is the science underlying the changes in color, texture, and flavor as cabbage transforms into sauerkraut? Why does milk thicken into yogurt, and how can the science of gelation help us understand and quantify the new texture? What can be deduced about the science of enzymes by studying mold fermentations such as amazake or koji? This block, in particular, tends to overlap with the following three blocks.

2.2.2. Block 2: Flavor—Physiology and Sensory Analysis. The second block of the course focuses on flavor. It is introduced in the form of informal tastings as soon as the students' earliest hands-on exercises begin to bear fruit. These tastings usually lead to many questions about how flavor works. How do humans experience it, and how can it be quantified as scientifically as possible? What are the challenges and complexities? With questions such as these, the students are introduced to flavor physiology and sensory analysis. They learn about taste and olfactory receptors, neurophysiological aspects, and important flavor experiments in the scientific literature.

This block features a visit by a sensory scientist and/or a field trip to a sensory analysis center, which helps bring the informal tastings to a more advanced level. The students are trained in sensory analysis performed via pen and paper or with software tools, and then apply their new skills to the class-produced fermentations. Students perform a Basic Taste Test, which probes a person's ability to detect the five basic tastes, and learn how to perform descriptive analysis, hedonic consumer tests, and attribute evaluation via Check-All-That-Apply surveys.[66,67] Students also learn about multisensory aspects of flavor, highlighting the complexity of the human flavor experience.[51]

During the year of the class-wide experiment on yogurt (Figure 1A), student sensory analysis found that thermophilic yogurts have thick textures and flavor notes of "tangy" and "tart", whereas mesophilic yogurts are thinner and taste "buttery" and "metallic". To illustrate the multisensory aspects of flavor, the class conducted a special collaboration with a music class from a neighboring university. After learning about the interplay between sound, music and flavor, students composed pieces of music for each type of yogurt. Students tended to use high frequency sounds to illustrate acidity, low frequency and "darker" sounds for "old/stable" flavors, and popping sounds for the tingly texture of carbon dioxide gas. This exercise provides a novel way to think outside the box of conventional observations and let students' imagination play a more prominent role.

2.2.3. Block 3: Molecules—Properties and Identification. The third block focuses on the molecules of fermented foods, with special emphasis on flavor molecules.[54,68] The concept of microbial metabolism and the properties of the most common fermentation metabolites are introduced as well as their effect on flavor, texture, and color in food fermentations. Examples include the variety of acids produced in sauerkraut, yogurt, and kombucha, including their slight variations in flavor, their corresponding pHs and pK_as, and the chemistry of how they affect the color compounds in the fermentation substrates. Students also learn about the chemistry of flavor molecules more generally: important functional groups and properties. Further, the curriculum covers the basics of the biochemical pathways for metabolism of carbohydrates, proteins, and fats, and how the resulting metabolites affect flavor in fermented foods.[54,69] All concepts are continually explored in the context of class-produced fermentations. By the time the curriculum reaches this block, students have become well aware that even relatively small differences in substrates, microbial strains, and fermentation time can produce variable sensorial outcomes—in this block they learn about the underlying scientific reasons.

An important goal of Block 3 is to obtain familiarity with identification techniques. This includes thin layer chromatography, liquid and gas chromatography (LC/GC), mass spectrometry (MS), and sometimes NMR. The course has an ongoing collaboration with the university's small molecule mass spectrometry facility, and other techniques are performed in the classroom or at nearby facilities. Figure 1B shows selected volatile compounds detected by GC-MS during the year of the multiweek yogurt experiment. Figure 1C shows the class LC-MS data organized into a Principal Component Analysis plot, allowing for the prediction of similarities between yogurts based on molecular compounds. An assignment prompted students to find the key flavors associated with the detected compounds and to analyze how the molecular makeup could inform the results from sensory analysis.

2.2.4. Block 4: Microbes—Communities and Characterization. The fourth and final block of the course focuses on the microbes of food fermentations. It explores microbial interactions, communities, successions, and characterization. Using techniques such as plating, microscopy, and sequencing, students explore the microbial basis of their fermented foods in hands-on exercises, while literature readings and short lectures provide an in depth theoretical perspective. This part of the course also features a sequencing specialist as a visiting speaker and a collaboration and field trip to the university's sequencing facility. Past visiting speakers have also included academic researchers specializing in characterizing the microbial communities of fermented foods such as cheese.[37]

As the culminating activity for this block in the course, students prepare their own fermentations for sequencing and analyze their results. Figure 1D shows the data from the class-wide experiment on yogurts. This gives the final piece of the puzzle: fermented foods that were created in the first block of the course, then subjected to sensory analysis in the second block, and finally analyzed for their molecular makeup in the third block, are now having their microbial communities revealed. Students analyze the data in the context of the literature. How do these four investigations inform each other? How do ingredient variations manifest in microbial and molecular profiles? How do microbial compositions affect flavor profiles? Analysis and discussion of questions such as these form the basis of this final class-wide assignment in the course.

2.3. Course Design: Pedagogy for Curiosity, Engagement, and Creativity

The design of the course aims specifically to foster student curiosity, and, by extension, engagement, learning, and creativity.[46,70−72] The goal is to give students a sense of empowerment and firsthand experience of how a topic can become accessible using the inquiry techniques in the course. It aims to show students how they can use their curiosity to dive deeper into a field, all the way to making a meaningful contribution to it. With this in mind, the curriculum follows an overall inquiry-driven and student-centered format, where students are constantly required to ask their own questions as a way of delving deeper into the material. They are given ample space to explore both theoretical and experimental answers to those questions and are in constant dialogue about the questions and answers with the instructor and their peers. In the process, students develop their skills asking "good" research questions. They receive continuous feedback from the instructor throughout the semester via socratic questioning that probes the feasibility of their questions and answers. They also receive indirect feedback through the organic process of attempting to answer their own and their peers' questions theoretically and experimentally. The skill is ultimately assessed by the quality and inquiry of the final project. The inquiry process eventually leads to a multiweek project phase with the ultimate goal of exploring questions that are substantive, original, and addresses questions whose answer would make genuine contributions to the field (assignments and class discussion prompts are available in the Supporting Information). The approach throughout the semester is as outlined below.

2.3.1. Individual Inquiry. The very act of signing up for a semester-long course or attending the first class meeting is an expression of curiosity. How can an instructor harness this

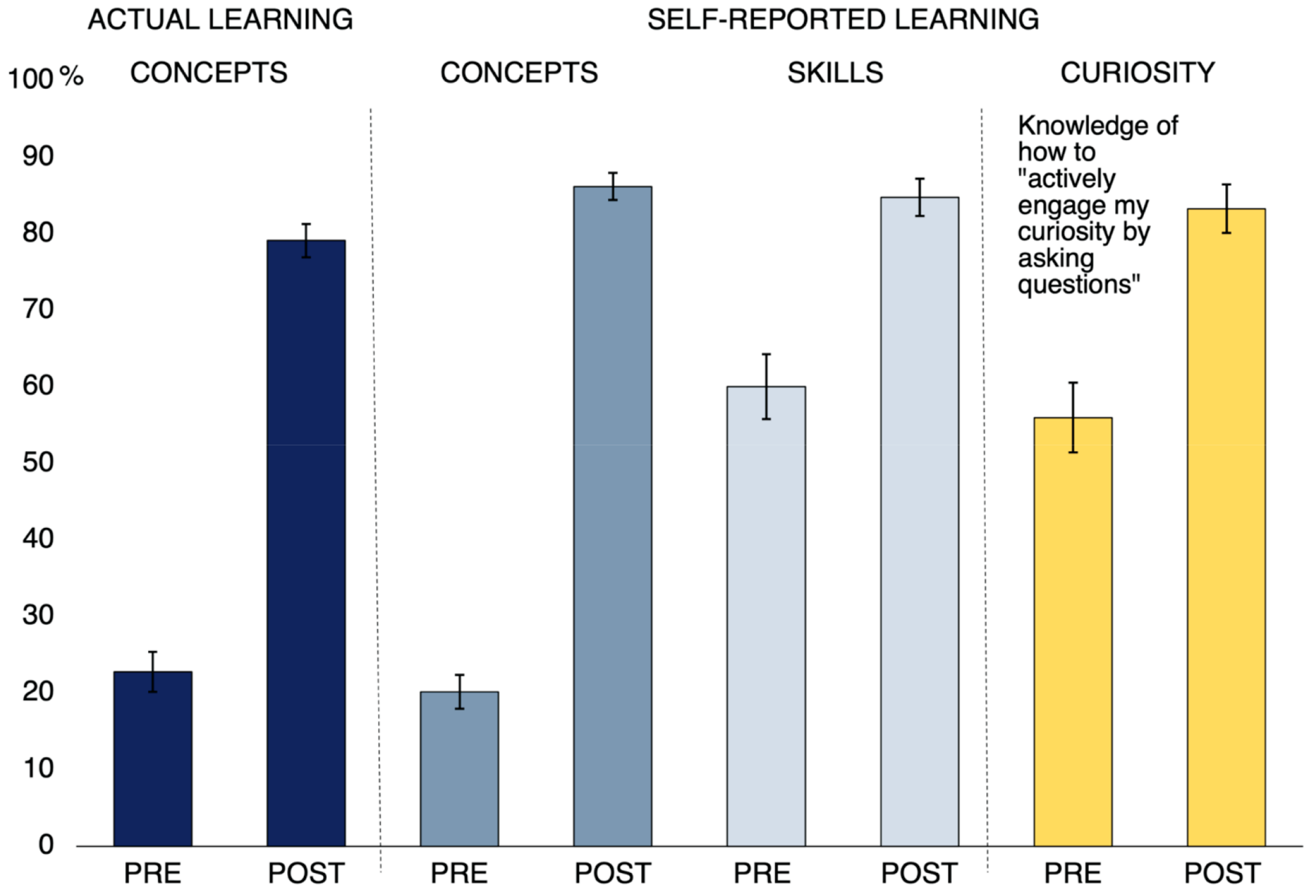


Figure 2. Students' actual and self-reported learning. Course outcomes as observed by pre- and post- tests for concepts (left), self-reported gains in concepts and skills (middle), and curiosity (right). There was a significant difference between pre- and post-tests/surveys for all four categories, $p < 0.0001$ ($N = 44$). Data shown are from two representative years of the course (2017 and 2021). Test- and survey tools, descriptive statistics, and disaggregate data are shown in the Supporting Information.

curiosity and not stifle it? Research shows that being encouraged to ask questions can lead to increased curiosity, engagement, and creativity.[46,73] With this in mind, students are encouraged to approach all hands-on class exercises with an "inquisitive mind", constantly asking questions about the procedure and outcomes. Students engage around these questions in class or in a discussion forum and perform independent literature research or propose experiments that help answer their own and their peers' questions. In the process, they begin to develop a sense for the characteristics of productive research questions and what answering them might look like. A version of this assignment are the "flash-presentations", which take place a few weeks into the semester, when each student explores a topic of their choosing and presents it to the class. Students are encouraged to stay engaged in other students' presentations by writing down questions and comments that they later post in the discussion forum (and, as time permits, in class). The presenter answers a subset of these questions in a follow-up assignment. The general theme is to give students the opportunity to reflect on what they are curious about before telling them the answers through lectures or readings, with the goal of making them aware of their curiosity and their desire to know more. Letting students' questions lead the way into the material also allows individual students to engage with their specific interests. By getting in the habit of asking questions early, students hone their inquiry skills and naturally begin to explore potential project ideas.

2.3.2. Class Inquiry. The individual curiosity exercises lead to class-wide experiments. As a group, the class explores a subset of the questions that have come up in the individual inquiry. The aim is to begin to model how a researcher might design hypotheses and experiments; thus further exploring the characteristics of feasible research questions. Class-wide experiments vary in scale from a single class meeting to many weeks. Past experiments have included how the ratios of yeast to bacteria vary in sourdough based on various parameters and the evolution of pH or alcohol in sauerkraut or mead. An example of a comprehensive multiweek project on yogurt is described in Figure 1. An important part of the class-wide experiments is to practice interpreting results and comparing outcomes to the literature.

2.3.3. Student Team Inquiry—Projects. After having acquired familiarity with the subject and practiced how to ask and answer questions, students apply and transfer what they learned in team-based projects. This is a chance to practice interdisciplinary team work in a creative context. It begins with brainstorming exercises and assignments, where students explore a few potential project ideas in more depth. The process is an ongoing cycle of feedback and adjustment from the course staff and peers that ends with the submission of a proposal. The resulting projects often draw on the team members' backgrounds and strengths.

2.3.4. Spontaneous and Creative Inquiry. Curiosity and creativity flourish with freedom to explore different options, and

https://doi.org/10.1021/acs.jchemeduc.2c01153
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the course encourages this as often as possible. There is always a wide variety of options for ingredients and topics, and students are encouraged to take an active role in the curriculum by proposing field trips, visiting speakers, and class experiments. With this follows a certain sense of adventure and spontaneity that keeps both students and instructors on their toes, all in all leading to a more engaged experience.

2.3.5. Modeled Inquiry—Inspiration from Professional Fermenters. Creativity and problem solving already play important roles in the field of fermentation. Many leading restaurants engage in fermentation research and development in their quest for novel flavors and recipes. The same is true for the food industry, where fermentation practices are constantly invented and optimized. Visiting speakers and field trips to local companies and organizations offer this perspective by exposing students to the creativity of others.

2.4. Student Learning

2.4.1. Actual and Perceived Learning of Concepts. The objective of this course is to teach interdisciplinary concepts in chemistry, biology, and other STEM disciplines using flavor and fermentation. The study's data show that students' knowledge of concepts increased significantly by the end of the semester; from a mean of 23% (SD = 17) on pretests to 79% (SD = 14; $t(43) = -20$, $p < 0.0001$) on post-tests, constituting an overall normalized learning gain of 0.73 (Figure 2, left).

Self-reported learning of concepts was somewhat higher, though still agreeing with the overall trend of actual concept learning: it increased from an average of ∼20% (SD = 15) before the course to 86% after (SD = 12; $t(43) = 27$, $p < 0.0001$), with an overall normalized gain of 0.83 (Figure 2, middle). Normalized learning gains ranged from 0.77 to 0.91 for different topics with the highest perceived gains on the individual presentation (Supporting Information). A potential limitation is that the tests for conceptual and perceived learning were only administered during two of the course's eight offerings. Some active learning courses have reported lower gains for self-reported than actual learning compared to traditional learning environments, citing the effect of increased cognitive effort as a possible explanation.[39,74] These courses tend to involve different survey instruments and educational settings, primarily being large-enrollment, introductory STEM classes, likely accounting for some of the difference. By contrast, CUREs, which in many ways have more in common with the course reported on here, have also shown gains in self-reported content learning.[43,49]

2.4.2. Perceived Learning of Skills. Students' self-reported learning of skills increased significantly; from a mean of 60% (SD = 28) on presurveys to 85% (SD = 16; $t(43) = -6$, $p < 0.0001$) on postsurveys, constituting an overall normalized learning gain of 0.62 (Figure 2, middle). This is lower than the learning gain for concepts. Since fermentation is an unusual topic in students' previous courses and, at least until recent years, also an uncommon topic outside of class, it is not surprising that students perceive that they learn a lot about the concepts. By contrast, most students have been exposed to scientific skill building in their previous coursework, perhaps making them perceive a smaller learning gain for skills than concepts. Seen from this perspective, a perceived learning gain of 0.62 for skills can be considered high, especially given the predominance of science-majoring upper-class students that were enrolled in the course. The author hypothesizes that this gain can be partially explained by the novel context in which science skills are practiced in this course. It is also possible that the course's emphasis on answering current outstanding questions in the field provides impetus for students to stretch their skill set regardless of background. Confirming this notion, student comments on the attitude survey (available in Supporting Information) included: "I learned how to apply scientific concepts I had only learned in lectures before". Another student noted: "I learned to think like a scientist and create experiments". Some reports from large-enrollment courses suggest that inquiry-based lab experiments may expose students to the "complexities and frustrations" of practicing scientists, thus leading to a lower perception of learning than traditional instruction.[39] By contrast, many CUREs, similarly to this course, show self-reported gains in scientific skills.[43,49]

2.4.3. Student Attitudes on Inquiry Learning. Students recognized that the inquiry-driven course format was beneficial to their learning. They were aware that they were practicing their skills of tapping into their curiosity (Figure 2, right), and 58% said that "asking questions" was "very useful" or "useful" for their "learning, understanding and engagement of the material" (Figure 3). Some reports show student resistance to nontraditional learning, especially in large-enrollment introductory science courses.[74,75] The opposite is true for CUREs which often show that students appreciate the inquiry format, not only for content learning and scientific skills, but also for confidence and interest in science.[43,49] The course discussed in this article shares elements of both types of courses: the first half of the semester relies on content delivery (albeit done in the style of open-inquiry), and the second half focuses on research. The author hypothesizes that the positive attitude to the inquiry format could be due to (1) attitudes to inquiry-based learning vary depending on course context: a small, elective course like the one described here may carry different expectations from large, required, introductory STEM classes. (2) The course format is clearly explained at the beginning of the course and continuously throughout the semester. Similar strategies have been suggested as being helpful in other active learning contexts.[76,77] (3) The course is usually oversubscribed and students are selected based on science background, seniority, and an explanation of why they want to enroll, thus potentially adding a selection bias as to who enrolls in the class. In addition, the teaching style is clearly stated on the syllabus and explained in the first class, giving less enthusiastic students a chance to

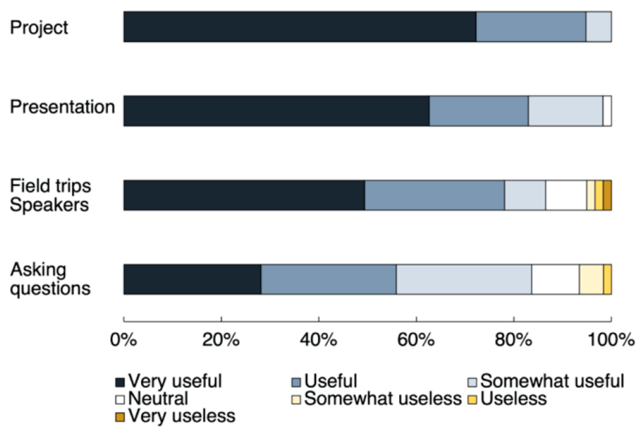

Figure 3. Student attitudes for how the different course assignments contributed to their learning and engagement with the material ($N = 72$, 62% response rate, collected for five years from 2017 to 2019 and 2021 to 2022). Survey tools are available in the Supporting Information.

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Table 2. Examples of Student Projects from Several Course Offerings

TYPE OF PROJECT	TOPIC	METHOD/RESULT
Build something	Automated mozarella maker	Build appliance that automatically adjusts temperature and mechical steps of the mozarella making process.
Build something Study a scientific question	Cheese cave	Build temperature and humidity controlled chamber for cheese ageing; study their effect on lactose content in cheese over time.
Study a scientific question	Calorie bioavailability increase by fermentation	A food source of lactic acid fermented fish leads to increased spawning in zebrafish compared to a food source of unfermented fish.
Study a scientific question	Fermentation with cell free extract	Can you carry out fermentation without live yeast cells but using only yeast extract? Debunking Eduard Buchner's experiment from 1857.
Create & study a novel fermented food product	Pro-biotic kombucha gummies	Develop edible gummies from kombucha by exploring different hydrocolloids and dehydration methods; demonstrated preserved pro-biotic properties in final product.
Create & study a novel fermented food product	Ancient Chinese beer	Recreate beer based on pottery remains from ancient China as published in PNAS 2016; study scientific properties and sensory profile.
Study a scientific question Solve a food system challenge	Koji as soil fertilizer	Koji addition to potting soil increases length and width of wheat grass.
Solve a food system challenge	University food waste fermentation manual	Collect information on major food waste sources at the university; explore repurposing via fermentation into novel food products; compile a guide/manual.

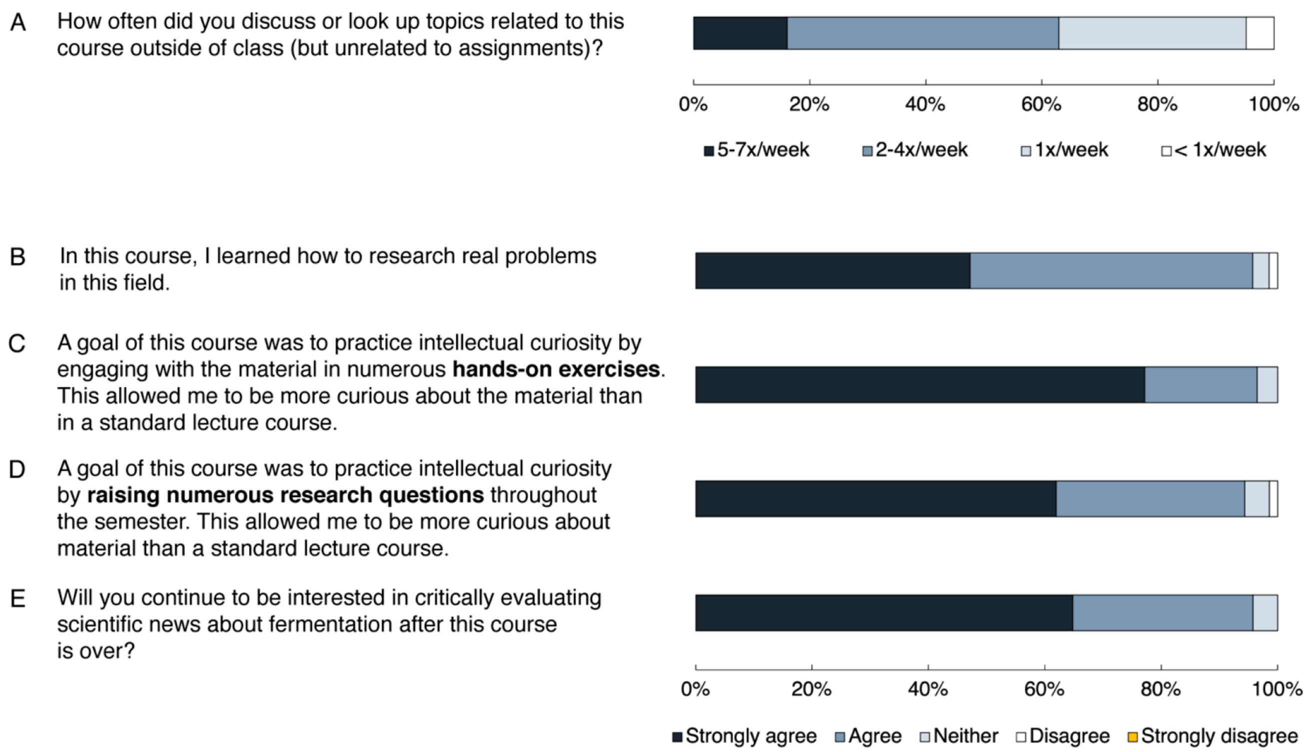

Figure 4. Student attitudes for curiosity and engagement. (A) How engaged were students outside of class? (B) How scientifically valuable did they find the research problems? (C, D) Did students find that the inquiry-based and hands-on format contributed to their learning and engagement? (E) Did they foresee continued engagement after the course was over? ($N = 72$, 62% response rate, collected for five years from 2017 to 2019 and 2021 to 2022). Survey questions are available in the Supporting Information.

unenroll, also contributing to the selection bias. This stands in contrast to required science courses, where students may not have a choice of whether they enroll or not.

2.5. Authentic Research Experience

2.5.1. Student Project Outcomes. An important goal of the course was to offer an authentic research experience that empowered students to access their curiosity and creativity while honing their ability to ask "good" research questions, all while contributing novel or meaningful results to the field. Examples of student projects are shown in Table 2.

The projects roughly fall in four different categories: build something, study a scientific question, create and study a novel fermented food product, and solve a food system challenge. An example: two seniors, a computer science major and a biology major, built a temperature- and humidity-controlled cheese cave and studied cheese aging. A second example: a junior applied math and computer science major designed novel fermentations and prepared a manual for the university based on the most common food waste products. During some course offerings, students have presented their projects at an institution-wide design fair at the end of the semester, thus disseminating their results beyond the classroom (similar to CUREs). This is not the case every year the small course is offered (dissimilar to CUREs but similar to some other discovery-based courses).

2.5.2. Student Project Attitudes. Students reported that the project was the most beneficial of all the course components for promoting their "learning, understanding, and engagement of the material". As many as 72% of respondents described the

https://doi.org/10.1021/acs.jchemed.2c01153
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projects as "very useful", and the rest found them "useful" or "somewhat useful" (Figure 3). It has been suggested that students perceiving research as having "scientific value" is an important element of research experiences.[78] The results from the present study's survey tools show that this was indeed the case: 96% of surveyed students either "strongly agreed" or "agreed" that the course had allowed them to learn "how to research real problems in this field" (Figure 4B), suggesting that even advanced science majors found a powerful context in which to apply and further develop their science skills. The sentiment is mirrored in a comment from a last semester biology major who noted that "this has been the first time where I felt like I had an idea in biology and (to some degree) made steps toward actualizing it". Previous studies report that students recognize the important role of research experiences on their personal and professional development.[9] It is also possible that the course's emphasis on student agency, and personal significance—the project ideation process was entirely student-driven —contributed to students' positive perceptions.[78] Similarly, the emphasis on the fact that "failed" experiments are an important part of scientific discovery was likely helpful.[39,79] For example, on open-response questions (available in Supporting Information), comments such as this one were common: "I felt empowered ... to attempt, research, fail—what a classroom should be".

2.6. Student Attitudes on Curiosity and Engagement

One of the main objectives of the course was to maintain and foster curiosity and engagement and by extension creativity.

A marker of both curiosity and engagement is the degree to which students voluntarily interact with and seek out more of the course material outside of class. Is it the subject of conversations with friends and family? Does it lead to unprompted searches on the Internet? The author found that as many as 95% of students reported that they "looked up or discussed course material outside of class but unrelated to assignments" at least once per week (Figure 4A). Of these, 47% reported doing it 2−4 times per week and 16% almost daily (5−7 days per week). A prompt to comment on their answer solicited remarks such as "my friends are probably sick of me" and "I explained how to make tempeh to all my friends". A limitation is that although the attitudes survey was administered over as many as five of the course's eight offerings, the response rate was lower (62%). The lower response rate can be explained by completion being completely voluntary, whereas completion of the test/survey for actual and perceived learning (Figure 2), where the response rate was higher (100%), counted toward participation credit.

Students recognized that the inquiry-driven course format was beneficial to their curiosity and engagement. The course promoted inquiry by (1) encouraging students to ask questions about the material and (2) engaging with the material in numerous hands-on exercises. A large portion of students (62% for (1) and 77% for (2)) strongly agreed that this "allowed them to be more curious about the material than a standard lecture course" (Figure 4CD). Similarly, 58% of respondents rated the question-and-answer assignments at the start of the semester as "very useful" or "useful" for "learning, understanding, and engagement" (Figure 3). Self-driven exploration and development of freely chosen topics were appreciated for promoting "learning, understanding and engagement". For example, the most highly rated assignments were the individual presentation and the project (Figure 3). Further, when asked in an open response question (available in Supporting Information) about what they thought were "the strengths of the course", 54% of responses included words such as "fun", "engaging", "excitement", and "intrigue", while 63% of responses alluded to the "research", "hands-on" format, and "open exploration". One student commented: "the hands-on experience is incredibly engaging and educational...[it] actually teaches you through experience and application". Another student commented: "few classes utilize spontaneity to inspire creativity and engagement. This class did". And a third student offered a comment on the course overall: "the level of engagement is uncanny compared to other courses".

During the semester, there was a 62% increase in students agreeing with the statement that they knew how to "actively engage my curiosity by asking questions" (Figure 1, right), and 65% strongly agreed that they would "continue to be interested in critically evaluating scientific news about fermentation after the course is over" (Figure 4E). In addition, when asked what they learned and how the course changed them, as many as 26%, without being prompted, referred to some aspect of "after" the course with wording such as "this course helped me just scratch the surface ...can't wait to follow up in the future" and "I will take the knowledge of fermentation and flavor that I learned in this class with me forever". And after taking the course "I view food differently", and have "a new passion for food science in my life"; the course has "kindled my interest in learning more on my own time". In summary, these findings suggest that the course was successful in setting the stage for future learning.

Although not studied formally for the purposes of this paper, it is the instructor's impression that many students did indeed continue to seek out further opportunities related to the course. One memorable example is a student who returned one year later with a jar of soy sauce that had been fermenting since preparing it in class. Other students have reported on their at-home fermentations: ranging from mead to pickled carrots. Most encouraging, several students later reported continuing to do more advanced research on the topics of the course later in their academic career.

3. CONCLUSION

In conclusion, this article describes the design and execution of a student-centered, inquiry-based science course. The course is novel in that it brings together flavor and fermentation, two topics that are not usually covered in the undergraduate curriculum. It applies these topics to the teaching of integrated interdisciplinary concepts in chemistry, biology, and other STEM disciplines. By emphasizing curiosity, engagement, creativity, and practicing how to ask "good" research questions, the course fills a gap in the traditional undergraduate research experience. Responses to the tests and surveys show that the course promotes student engagement and curiosity as well as gains in conceptual learning and in self-reported learning of concepts and science skills. Further, students report valuing the hands-on and inquiry-based format for improving their learning, engagement, and sense of curiosity about the material.

4. METHODS

4.1. Population and Setting

The course is offered within the undergraduate curriculum of a large R1 research institution in the northeastern United States (Harvard University). From 2015 to 2022, a total 196 students have been enrolled in the course, with 20−32 students per offering every spring semester. A majority of the students

(82.7%) have been seniors, followed by 11.7% juniors, 4.1% sophomores, 0.5% first-year students, and 1.0% master's degree students. Students were enrolled in the course as an elective (88.7%), or to fulfill a requirement for a major or secondary major (11.9%). The majority of enrollees were science majors, with the breakdown across all fields as follows: Biology and Bioengineering (40.5%), Chemistry (10.6%), Engineering and Physics (13.4%), and Computer Science, Statistics and Applied Math (16.5%). Remaining students were majors in the social sciences (12.4%) or humanities (6.6%). In addition, 57.7% identified as female and 41.8% as male. The Institutional Review Board (IRB) of Harvard University determined that the research conducted for this study was not human subjects research as defined by DHHS regulations.

4.2. Assessment of Conceptual Understanding

Conceptual understanding was assessed with a written test that was administered before the first class meeting at the start of the semester and again at the end of the semester (after the last class meeting but before students knew their course grades). Both tests contained identical questions covering the course's core concepts (available in Supporting Information). Students were encouraged to complete the test for participation credit. Tests were administered in 2017 and 2021 ($N = 44$; 100% response rate). Normalized learning gains were calculated according to Hake,[80] where the average normalized gain $\langle g \rangle$ is defined as the average gain for the course divided by the maximum possible average gain for the course, i.e., $\langle g \rangle = (\%\langle \text{posttest} \rangle - \%\langle \text{pretest} \rangle)/(100 - \%\langle \text{pretest} \rangle)$.

4.3. Assessment of Student Perceptions

Perceived learning: Students' estimation of their perceived learning was measured with a pre- and postcourse survey with questions relating to (a) concepts and (b) skills (available in Supporting Information). The survey was administered in 2017 and 2021 ($N = 44$; 100% response rate). Students were encouraged to complete the survey for participation credit. Perceived learning gains were calculated according to Hake,[80] where the average normalized perceived gain $\langle g \rangle$ is defined as the actual average perceived gain divided by the maximum possible average perceived gain, or $\langle g \rangle = (\%\langle \text{postsurvey} \rangle - \%\langle \text{presurvey} \rangle)/(100 - \%\langle \text{presurvey} \rangle)$.

Attitudes: Student perceptions of their learning and engagement was assessed with a post-test survey that was administered for five years, from 2017 to 2019 and 2021 to 2022 ($N = 72$; 62% response rate) (Supporting Information). Students were encouraged to complete the survey, but participation credit was not mentioned. Data from the spring of 2020 have been excluded due to curricular changes during the onset of the Covid-19 pandemic.

4.4. Statistical Analysis

All statistical analyses were carried out with Microsoft Excel. Independent *t* tests (paired two-sample for means) were used to determine the statistical significance for concepts and perceived learning. All error bars denote the Standard Error of the Mean (SEM).

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.2c01153.

Syllabus, equipment and materials, assignments, hands-on exercises, study tools, and descriptive statistics (PDF, DOCX)

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Notes

The author declares no competing financial interest.

■ ACKNOWLEDGMENTS

The author would like to thank all past students in the course, as well as former teaching assistants Mai Nguyen, Patricia Jurado Gonzalez, Julia Espeso, and Alejandra Touceda. The author also thanks Maija Greis for developing and leading the sensory analysis exercises, Sunia Trauger, Charles Vidoudez, and Jennifer Wang and the Harvard Small Molecule Mass Spec Facility for hosting fields trips and for technical support, and Claire Hartmann and the Harvard Bauer Core for hosting and technical support. In addition, the author is grateful to Ben Hogue and students at Berklee College of Music for the multisensory music collaboration, and the following visiting speakers for having visited or hosted the class on field trips: Sandor Katz, Rachel Dutton, Ben Wolfe, Bill Nestor, Diego Prado, Blanca del Noval, Roy Desrocher and Tufts Sensory Analysis Center, Renae Conolly, Stephen Conolly, Rich Shih, Christina Agapakis and Ginko Bioworks, Roberto Flore, Formaggios Kitchen, Aeronaut Brewery, Ramon Perisé at Mugaritz, Arielle Johnson, Jason White at Noma, Aaron MacDougall and Broadsheet Coffee, and Taza Chocolate.

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