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Spectroscopic Methods for Pollution Analysis—Course Development and Delivery Using the Integrated Course Design Framework

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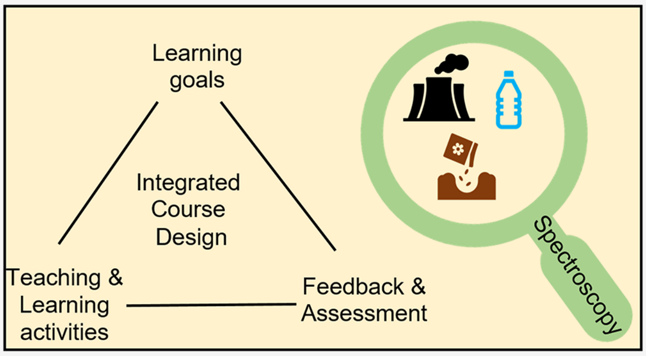

ABSTRACT: Amidst ongoing attempts to enhance green chemistry education in the chemical sciences curriculum, the teaching of analytical methods, such as spectroscopy, still largely lacks grounding in the principles of green chemistry. In an attempt to embed this context to spectroscopy education, this article describes the development, delivery, and evaluation of a course module designed to teach spectroscopic methods within the context of pollution analysis. Using the Integrated Course Design framework, a course section that intertwines fundamental spectroscopy knowledge with the application to pollution analysis was developed. Following the design and delivery of diverse teaching and learning activities, the analysis of student feedback revealed a high degree of satisfaction with the course. Some reservations around digital learning resources and group work activities present scope for improvement. This paper also describes the use of a multifold student assessment model developed on the basis of spaced repetition learning.

KEYWORDS: *Spectroscopy, Integrated Course Design, Pollution Analysis, Green Chemistry Education, Analytical Methods*

INTRODUCTION

Higher education is increasingly embedding principles of education for sustainable development. In this backdrop, chemistry education has also witnessed transformations, with the emphasis on green chemistry particularly since the turn of the millennium.[1−3] Research on sustainable and environmentally benign ways to transform molecules to products of value is now finding space in the mainstream chemistry curriculum.[4−6] This progress maps onto several UN Sustainable Development Goals (UNSDGs), including but not limited to UNSDG 7 (Affordable and clean energy), UNSDG 9 (Industry, Innovation and Infrastructure), and UNSDG 12 (Responsible production and consumption).

One of the 12 principles of green chemistry is centered on analytical methods for pollution prevention.[7] Specifically referred to as the principle of "Real-time analysis for pollution prevention", this principle calls for the development and utilization of appropriate analytical methods for real-time, in-process monitoring and control of hazardous substances.[7] This illustrates the important role of the chemical sciences discipline in environmental pollution analysis and abatement, thereby mapping various UNSDGs that relate to the biosphere: UNSDG 13 (Climate action), UNSDG 14 (Life below water), and UNSDG 15 (Life on land). The diverse instrumental methods available in the analytical chemistry toolbox—ranging from spectroscopy and electrochemical analysis to chromatography—have always been a part of the chemistry curriculum but have rarely been taught in the context of pollution analysis. For example, there are several examples of teaching of spectroscopic techniques contextualized to studying reaction mechanisms and kinetics.[8−12] However, the pedagogical literature on the application of spectroscopic techniques for pollution analysis is scarce. Performing a key phrase search of "Spectroscopic techniques for pollution analysis" on databases of chemical education journals, such as the *Journal of Chemical Education*, returns only a few related results demonstrating a clear gap in the literature. While analytical methods are extensively used in state-of-the-art pollution research, this has not filtered into the curriculum as prominently as some of the other aspects of sustainable or green chemistry. This comes amidst recent calls for chemistry education to address analysis of pollution and chemical hazards posing significant societal issues, especially in "least developed countries".[13]

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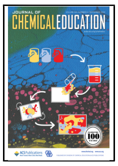

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Recent attempts to bridge the gap have been primarily through lab experiment/activity proposals. These include infrared (IR) spectroscopy for plastic waste analysis[14] and NOx reduction catalysis[15] and fluorescence fingerprinting of pollution sources in surface water.[16] These reports build on similar articles sporadically published in the past, which include using differential optical absorption spectrometry to measure atmospheric pollutants[17] and inductively coupled plasma (ICP)-methods to study metal deposition in environmental samples.[18]

While these laboratory experiments are a step in the right direction, there is a necessity for a more high-level curriculum design and delivery perspective of the same topic. The endeavor is to go from stand-alone laboratory exercises to designing a module or course section that introduces the theory of spectroscopy and proceeds to present their applications in diverse pollution analyses. This approach of coupling fundamental spectroscopy theory to pollution applications is consistent with the broader didactic approach for green chemistry education, which recommends integrated and embedded instruction.[2,3,19] Furthermore, such a holistic course design approach can facilitate the incorporation of new and innovative teaching/learning materials reported in the pedagogical literature. Some examples of this within the remit of spectroscopy include 3-D printable smartphone spectrophotometers,[20] and virtual reality (VR) experiences for IR spectroscopy[21] and X-ray fluorescence (XRF).[22]

When it comes to course development, several theoretical frameworks can be leveraged to inform the design process. A commonly used framework is "Backward Design",[23] which as the name suggests advocates course design to commence with the final picture in mind i.e., the student learning goal(s) and work backward to develop student assessments and teaching and learning activities. Building on this model, the "Integrated Course Design" (ICD) framework advocates for a simultaneous and integrated consideration of course components (learning goals, assessments, and teaching/learning activities) instead of a linear approach. The ICD framework splits course design into three phases, which focus on building strong primary components, assembling them into a coherent whole and finally addressing tasks on grading and course evaluation.[24] These are simply called the initial, intermediate, and final design phases, respectively (Figure 1). The inbuilt element of integration in the ICD model makes it a good fit for designing courses at the nexus between theoretical chemistry and applied green chemistry, like the one being considered herein on spectroscopic methods for pollution analysis. Furthermore. the ICD framework is consistent with the iterative ADDIE (Analyze-Design-Develop-Implement-Evaluate) instructional methodology.[25] This is important because it can inform the continuous improvement of the course through closure of competence gaps (initial design phase in ICD and "Analyze" stage in ADDIE) identified from course performance and evaluation (final design phase in ICD and "Evaluate" stage in ADDIE); thereby, an iterative feedback process can be built in to the ICD framework.

By presenting the design and delivery of a course on spectroscopic methods for pollution analysis modeled on the ICD framework, this article attempts to address the paucity of reports on integrated courses for such topics in the chemical education literature. In addition, the analysis of course evaluation and student performance data helps to identify important lessons for further refinements of the course. Hence, the ideas, resources, and recommendations presented herein can be adapted for delivery by higher education practitioners in chemistry classrooms elsewhere.

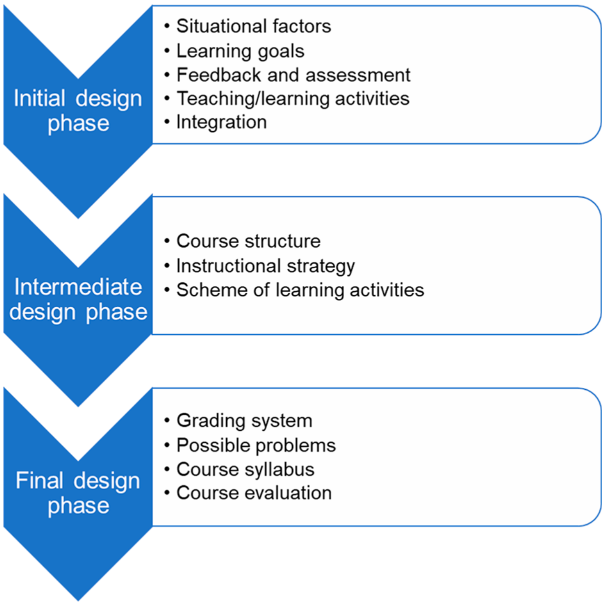

Figure 1. Main design phases of the Integrated Course Design (ICD) framework.[24]

INITIAL DESIGN PHASE

The initial design phases commences with an analysis of the "situational factors"[24] of the course. These are usually not within the control of the instructor but need to be accounted for as part of course design. Starting with the organizational context of the course, the spectroscopy content was to be delivered as part of a 15 credit module (1 credit corresponds to 10 h of learning including private study hours) titled "Pollution Sampling and Analysis" to a small M.Sc. Energy and Environment cohort (24 students). The module aims to cover topics of pollution sampling, and spectroscopic and chromatographic techniques for pollution analysis. With the module spanning 11 weeks in the autumn semester, the spectroscopy content was expected to be covered in 4 weeks (Weeks 3 to 6). A breakdown of student engagement hours for the spectroscopy section of the course module is provided in the Supporting Information (Section S1 and Table S1). Linking the importance of pollution analysis to sustainability challenges was done upfront in the introduction of the course module. Since the course was designed for the 2022/23 academic year, COVID-19 did not impose any constraints on mode of delivery, with the instructor having full freedom to select the blend between in-person and remote instruction. This decision could be informed by recent advances in blended learning environments reported for spectroscopy education.[26−28]

Turning to the "characteristics of the learners",[24] the M.Sc. Energy and Environment program, has broad entry considerations—a bachelor degree in engineering, physical sciences or mathematics is required. Hence, while spectroscopy falls within the remit of chemical science, students with very little exposure to chemistry at the undergraduate level would also be eligible to be on the course. The cohort is a mix of home-school (UK) and international students, with the latter being the majority. The "nature of the subject" is largely application-based with the focus being on the use of spectroscopic techniques for pollution analysis. This however does require a basic theoretical

Table 1. Alignment of Learning Goals/Objectives with the Teaching or Learning Activities and Assessment Methods for the Course on Spectroscopy Methods for Pollution Analysis

Learning Goals/Objectives	Teaching or Learning Activities	Student Assessment
To describe the fundamental principles of spectroscopy and different spectroscopic methods	Short video recordings of factual information	Formative MCQ quizzes
	Padlet student-formulated questions	Summative MCQ test
	Bite-size concepts using PowerPoint slides—theory	
To apply spectroscopy knowledge to the analysis of environmental pollutants	Lectures: Bite-size concepts using PowerPoint slides—introduction to applications	Summative MCQ test
	Applications in a Think-Pair-Share construct at lectures:	
	• Indoor settled dust and air quality (IR spectroscopy)	
	• Mercury sensing using gold nanoparticles (UV−visible spectroscopy)	
	• Heavy metal toxicity in water (AAS, FES, XRF, and ICP methods)	
	Tutorials for problem-based learning:	Summative OTLA
	• Emissions from wood burning stove (FTIR spectroscopy)	
	• Calibration of spectroscopy equipment for quantitative estimation of a pollutant (AAS, FES)	
	In-lecture demonstration:	
	• Lead in soil (portable XRF)	
	Laboratory practical:	Summative lab report
	• Phosphate in soil (colorimetry: UV−visible spectroscopy)	
	• Lead in soil (AAS)	
To develop spectroscopy-based analytical approaches for pollution analysis pertaining to global challenges	Sticky-note brainstorm at lectures:	
	• Portable emission systems for vehicle exhaust (IR and UV−visible spectroscopy)	Summative OTLA
	Literature analysis in a flipped classroom:	
	• Analyzing microplastic pollution (IR, UV−visible, AAS, XRF, and ICP methods)	Formative group discussions and presentations

understanding of the relevant spectroscopic methods. All of these factors will inform the three components of constructive alignment described below, starting with the learning goals/objectives (LOs).

For the formulation of learning goals, the ICD framework proposes six types of "significant learning", which can be visualized as a cross between the cognitive and affective domains of Bloom's taxonomy.[29] These are foundational knowledge, application, integration, human dimension, caring, and learning how to learn.[24] The three LOs developed for this course (Table 1) explicitly map onto the first three types—knowledge, application, and integration—in the same order. The affective aspects of what values students will adopt is underpinned by the context of environmental pollution in the second and third LO. This is further underscored by the "global challenges" phrase in LO3 (Table 1) that provides a grounding in human values to make students feel more passionately about pollution. In this regard, the ICD framework demonstrates potential for fostering systems thinking competency in students; learning goals spanning the different types of "significant learning" can help students integrate core chemistry knowledge (for example, spectroscopic methods) with the sustainability of earth and societal systems.[19,24,30]

The ICD framework advocates for forward-looking "educative assessment" instead of backward-looking "auditive assessment".[24] With the aim of designing questions that replicate "situations in which students are likely to use what they have learned",[24] the topical issue of microplastic pollution was considered. Students need to be competent in devising strategies to analyze microplastic pollution, which in a professional working environment is attempted with unrestricted access to information including online resources. Acknowledging the importance of replicating this environment in summative student assessment practice, such questions that assess higher levels of Blooms taxonomy (analyze, evaluate, and create)[29] were designed for an open-book assessment format, referred to herein as an Online Time Limited Assessment (OTLA). Another piece of "educative assessment" considered was a technical report requiring students to articulate laboratory practice and quantitative data processing for pollutant determination.

For student "self-assessment", online formative assessments in the form of weekly multiple choice questions (MCQ) quizzes were designed. As feedback, the correct answers to each MCQ quiz were released at the end of the week. Furthermore, written feedback would be provided on the lab report before students took the final summative OTLA. A more rigorous check for the alignment of the assessments considered with the identified LOs was done after exploring the teaching and learning activities for the course.

Teaching and learning activities need to encourage active learning across the three modes of learning in the ICD framework: (i) information and ideas, (ii) experience, and (iii) reflective dialogue.[24] To engage students in experiential and reflective learning at in-person teaching sessions, some factual information would need to be delivered prior hand. This content was packaged as short video recordings (approximately 15 min long) that students had to watch before the lectures. Subtitles/captions were made available to improve accessibility especially for international students.[31] To promote "reflective dialogue" after engaging with the online resources, students were asked to anonymously post self-formulated questions on "Padlet" (Table 1).

At in-person lectures, examples of environmental pollution were first introduced from the perspective of challenges to a sustainable future, as a bridge to spectroscopic techniques. Active learning at lectures was to be fostered through a variety of constructs, including think-pair-share and sticky-note storm, to

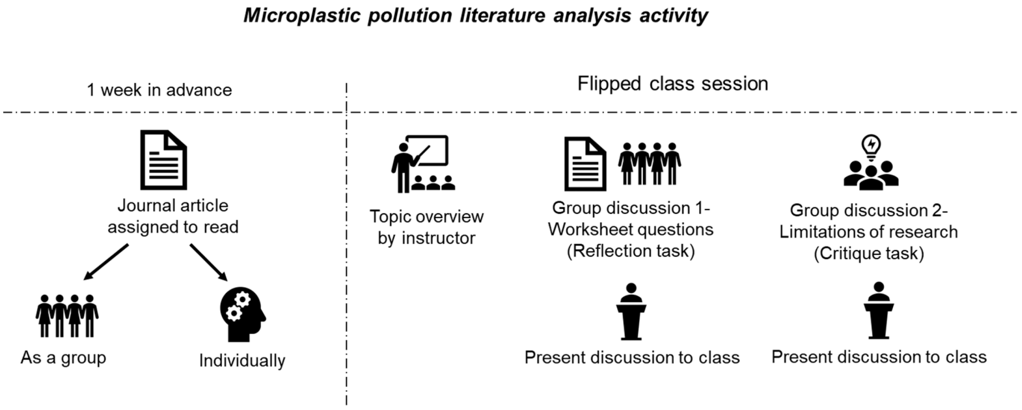

Figure 2. Delivery of the microplastic pollution literature analysis activity.

Table 2. Course Structure for the Spectroscopy Section of the Module

	Week 1	Week 2	Week 3	Week 4
Prelecture	Video: Introduction to spectroscopy	Video: FTIR Instrumentation	Video: AAS Instrumentation	Microplastic pollution literature reading
Lecture	Introduction; IR and UV−visible spectroscopy	FTIR, UV−visible spectroscopy, AAS, and FES	FES, ICP, and XRF	Microplastic pollution flipped class activity
Tutorial	Error analysis	FTIR data analysis	Calibration methods	–
Lab practical	Soil sample preparation and acid digestion[a]		UV−vis analysis for phosphorus and AAS analysis for lead in soil sample	

[a] The related theory for this was to be delivered in the preceding week on pollution sampling.

discuss pollution-related applications (Table 1) in a research-led teaching approach (Section S2 in Supporting Information). Typical examples of how these constructs were used at lectures are provided in Section S3 of the Supporting Information. Nevertheless, these active learning techniques still do not contribute to a "direct doing experience" as per the ICD lexicon.[24,32] This was set to be achieved through laboratory practical sessions[20,33] (Section S4 in Supporting Information) and demonstrations using portable equipment (Table 1). Complementing the qualitative treatment of these applications, basic quantitative competence around calibration and data processing for spectroscopic applications were delivered through tutorials using a problem-based learning approach for the entire cohort[34,35] (Section S5 and Table S2 in the Supporting Information).

A literature analysis-based learning activity was designed on microplastic pollution for students to be able to integrate their competence with the different spectroscopic methods (Figure 2). The activity was delivered in a flipped class environment, with student groups being assigned a journal article to read on microplastic pollution in advance. Journal publications were selected to evidence recent research from different countries (Section S6 and Table S3 in the Supporting Information). This was envisioned as a subtle approach to decolonizing the curriculum and creating a more inclusive educational experience for a cohort with a high proportion of international students. On the day of the session, the instructor provided a brief overview of microplastic pollution, followed by two rounds of group discussion (Figure 2). In the first round, students reflected as a group on the main findings of the research article and the use of different spectroscopic techniques. In the second round, students discussed the limitations of the study and brainstormed recommendations for a more reliable analysis of the pollutant(s). After each round, a representative from each group presented the discussion to the class; this allowed collation of ideas, peer group learning and oral feedback to be provided by the instructor. Hence, this activity taps into all three modes of active learning of the ICD framework.[24]

The final step of the initial design phase is checking for "integration" of the learning goals, assessment and learning activities by following the principle of constructive alignment.[36] Table 1 illustrates the use of diverse teaching and learning activities and assessment methods to support and evaluate student attainment across all identified LOs. LO1 focuses on fundamental knowledge of spectroscopy delivered through digital learning resources and at in-person lectures. Formative MCQ quizzes were designed as a preparative tool to eradicate misconceptions (Section S7 in Supporting Information). LO1 also necessitates a closed-book summative MCQ test to evaluate the attainment of basic competence in spectroscopy and spectroscopic methods. Having this as the first piece of summative assessment would enable the delivery of feedback that can inform student preparation for the subsequent pieces of summative assessment targeting more advanced learning outcomes.

A wide variety of teaching/learning activities aligns against LO2 (Table 1). This includes a "doing experience" of lab-based practical work,[24] which is assessed through a written report. In addition, the ability to "apply" spectroscopic methods for pollutant analysis can also be evaluated in the summative OTLA. LO3 requires critical thinking and the ability to integrate knowledge acquired in the course. The training for this competence includes a brainstorming session and a literature analysis activity (Table 1). These exercises are done with full access to information sources, and consequently, this LO is best assessed in an open-book environment (summative OTLA, Table 1).

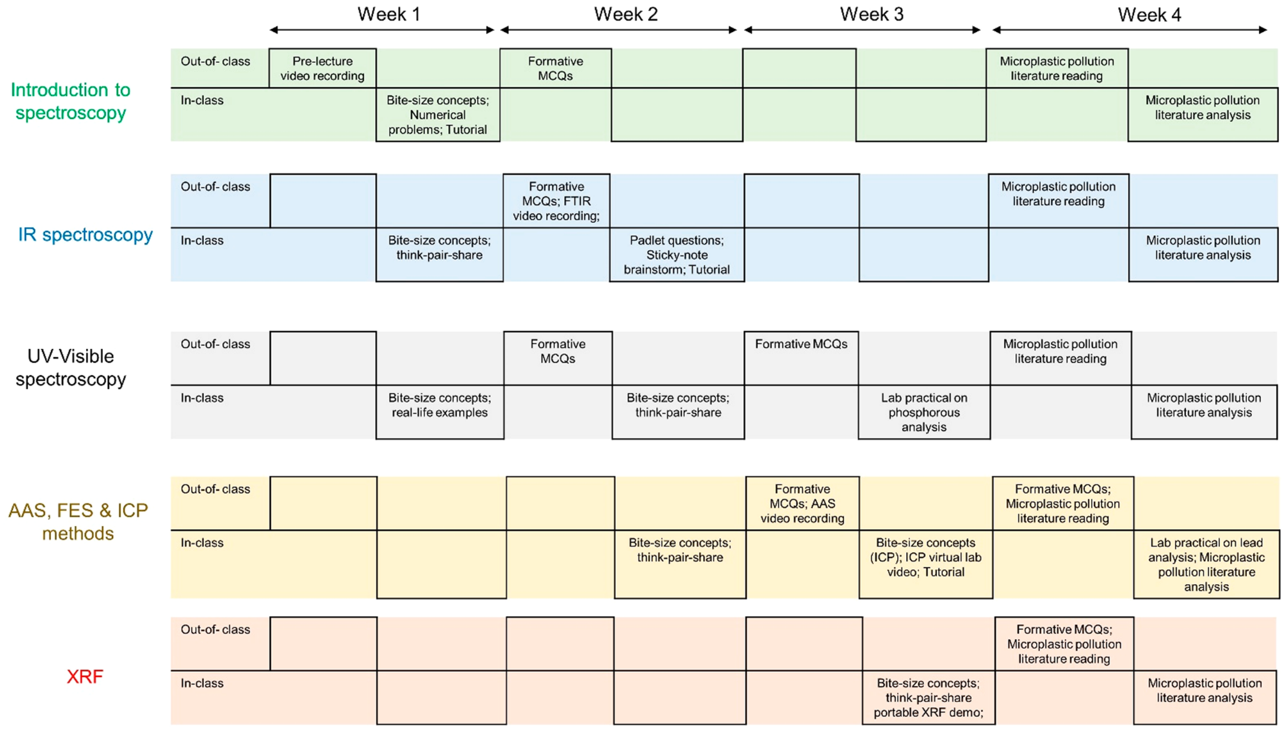

Figure 3. Overall scheme of topic-wise learning activities represented as a "castle top" diagram as per ICD framework.

INTERMEDIATE DESIGN PHASE

This phase begins with creating a course structure that captures the sequence of topics to be covered (Table 2). The spectroscopic methods taught in this course were sequenced in the following order: IR, UV−visible, Atomic Absorption Spectroscopy (AAS), Flame Emission Spectroscopy (FES), ICP methods, and XRF. This order goes from low to high energy excitations, i.e., from rotational and vibrational excitations to electronic excitations. Since the course would begin with an introduction to spectroscopy and the electromagnetic spectrum, the aforementioned sequence represents a logical learning pathway. Although the techniques are quite distinct, there is also significant common ground in terms of their integration as part of a wider spectroscopy toolbox. Pigeonholing each spectroscopic method in a weekly bucket could promote knowledge siloing; consequently, the course structure has several spectroscopic methods spread over multiple weeks (Table 2). Furthermore, the literature analysis activity on microplastic pollution is designed as the synoptic exercise for the final week of the course.

Table 2 provides a high-level view of the sequence of topics under four categories: prelecture engagement, lectures, tutorials, and lab practical sessions. This needs to be integrated with an "instructional strategy" to produce an "overall scheme of learning activities".[24] Using the list of teaching and learning activities identified earlier (Table 1), Figure 3 sketches a "castle top" sequence of these activities for each topic against a weekly timeline as recommended in the ICD model. The figure demonstrates the sequence of in-class and out-of-class activities and how they build on each other. The wide variety of in-class learning activities help address the "differentiation" aspect of course design.[24] The out-of-class activities include videos for prelecture engagement and formative MCQ quizzes for postlecture self-assessment. This is the common structure except for the last week, where students undertake the literature reading exercise ahead of the flipped class session. The literature analysis exercise maps onto all the topics covered on the course, thereby addressing the "integration" aspect of course design[24] and provides a good closure to the spectroscopy course section.

FINAL DESIGN PHASE

The final design phase is primarily concerned with developing a grading system for the proposed assessments and ways to evaluate the course and the teaching.[24] Besides the alignment to the respective LOs and learning activities to student assessment (Table 1), the timing of the three summative assessments (MCQ, lab report, and OTLA) was considered to engage students in spaced repetition learning.[37] The summative closed-book MCQ test was to be held at the end of the 4 weeks of spectroscopy content delivery, following the weekly formative MCQ quizzes that were provided during the teaching period. The summative test contributed to 10% of the overall module mark, and feedback was to be provided immediately after the conclusion of the test. In a little over a week after this test, the lab report was due to be handed in, which carried 30% weight for the overall module mark. Finally, the open-book OTLA, which contributed to 50% of the module mark, was held in the University's exam period after the conclusion of the semester and comprised questions from the entire course module. The spectroscopy content contributed to 25% of the OTLA (i.e., 12.5% of the overall module mark). In line with University regulations, students require an overall score of 50% to pass the module, but a minimum mark is not required in each assessed component.

By embracing spaced repetition, the emphasis is not on placing factual information in the long term memory of the student; rather, the aim is to give multiple opportunities to students to think and apply concepts along their learning trajectory. These measures prepare students for the challenge of open-ended questions, where they not only have unconstrained

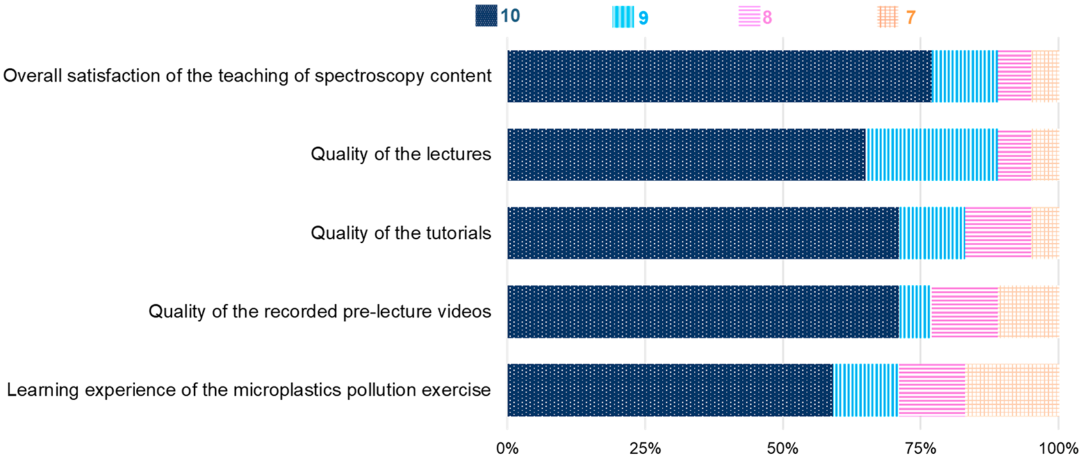

Figure 4. Student ratings (on a scale of 1 to 10 with 10 being the highest) of the quality and satisfaction of the spectroscopy teaching in the course.

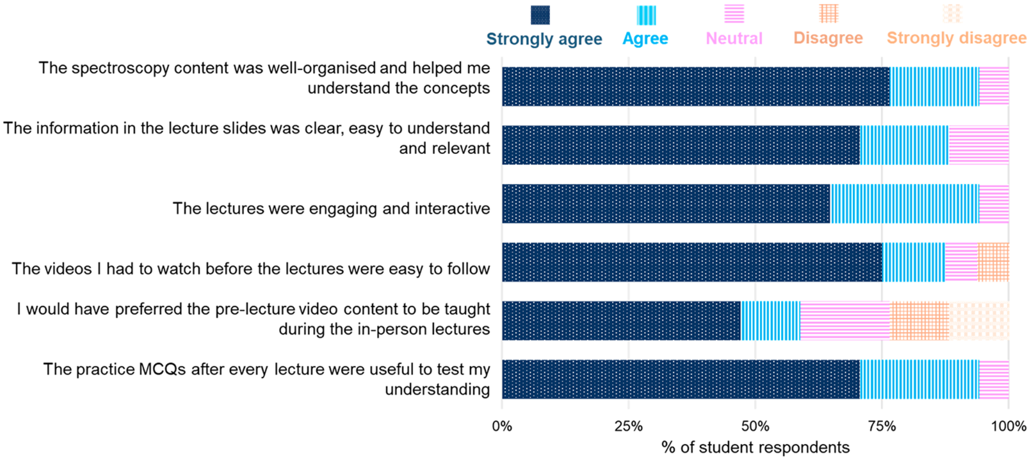

Figure 5. Student responses to Likert-scale statements on course content, lectures, prelecture videos, and formative MCQs.

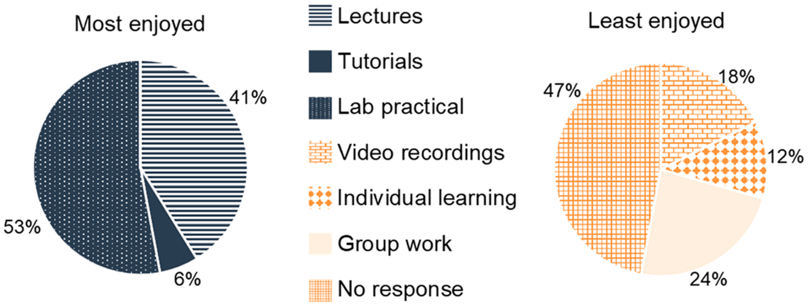

Figure 6. Modes of learning students most and least enjoyed in the course. One option for most and least enjoyed could be chosen from the following six options: lectures, tutorials, lab practical, video recordings, individual learning, and group work. Students could also skip the question or answer it partially, i.e., answer only most enjoyed or only least enjoyed.

access to factual "knowledge" but by which time have also been empowered with the necessary skills to leverage the access to such knowledge to solve complex problems.

The skew in the relative weights of each piece of summative assessment is in line with the growing emphasis on authentic assessments.[38−40] The MCQ test was designed to address fundamental competence on spectroscopic methods and their applications, which once attained, would facilitate the attainment of higher-order LOs assessed through the lab report and the OTLA. Hence, a multifold assessment model is used to evaluate LOs of varying complexity at various time points of the course.

Two sources of data—student satisfaction and student performance—were to be used for course evaluation. Student voice was captured through an anonymous online student satisfaction survey at the end of the spectroscopy section of the course. The organization of the survey, data collection, and analysis was done in line with ethical considerations and approved by the University of Leeds Research Ethics Committee. The voluntary survey, which took approximately 10 min to complete, was run on the "Online surveys" platform. Analysis of survey data and student performance in the formative and summative assessments is performed to identify elements of the course that worked well and recommendations for further iterations of the course, also pitched at educators wanting to adapt this content for delivery elsewhere.

■ STUDENT SATISFACTION

The survey response rate was 71% (17 of 24). Course delivery was largely well received by students with 77% of survey respondents rating their overall satisfaction of the teaching a perfect 10 on 10 (Figure 4). Since the ratings do not follow a normal distribution, standard deviation analysis is not presented; instead, the ratings are presented as a clustered bar chart (Figure 4). 94% of the respondents either "agreed" or "strongly agreed" that the content was well-organized and helped them understand the concepts (Figure 5). Hence, from a learner perspective, the sequence of activities captured in the castle-top diagram (Figure 3) has come through as being coherent.

When asked to rate the quality of the lecture and tutorial sessions, 65% of students rated the lectures a perfect 10, with the equivalent number being comparable for tutorials (71%) (Figure 4). As elaborated earlier, lectures explored applications of spectroscopic techniques in a qualitative manner, while tutorials engaged students in problem-based learning coupling acquired knowledge with basic mathematical skills for pollution analysis. Despite their identical quality ratings, lectures are a clear winner over tutorials in terms of popularity among students. When picking the mode of learning they most enjoyed, 41% chose lectures as opposed to 6% for tutorials (Figure 6). The diversity of the student cohort was identified as a key "situational factor" in the initial design phase (vide supra), and differences in student competence of mathematical techniques (algebra, calculus, and graphs) would need to be considered carefully in future iterations of tutorials on this course.

An overwhelming majority (94%) either "agreed" or "strongly agreed" that lectures were engaging and interactive (Figure 5). This can be seen as a direct verdict on the different learning activities embedded in lectures to promote engagement (Table 1). Students were largely satisfied with the quality of the videos offered for prelecture engagement, evident in the average rating of 9.4 (Figure 4). This notwithstanding, 18% of students chose video recordings as the mode of learning that they least enjoyed on the course (Figure 6). Considering that 47% of respondents did not submit a response for the mode of learning they disliked, 33% of students who did submit a response ended up choosing video recordings as their "least enjoyed" option (Figure 6). In comparison, neither lectures nor tutorials received a single vote in this category, consistent with findings in the wider literature of face-to-face teaching enjoying a renaissance in a post COVID-19 world.[41,42]

With a large majority "agreeing" or "strongly agreeing" that the video recordings were easy to follow (Figure 5), it is safe to conclude that neither the quality nor the level of difficulty contributed to the lower popularity of video recordings. This illustrates a decoupling between quality satisfaction and preferred learning pathways: the high degree of satisfaction with the quality of the digital learning resources coexists with a strong preference for in-person teaching activities. Close to 60% also stated a preference for the video content to be taught in in-person lectures (Figure 5). Although this content mostly constitutes "factual information", the feedback warrants a nuanced analysis of the dichotomy of "information delivery" and "insight building", which were assigned for asynchronous and synchronous learning pathways on this course. Going forward, increasing opportunities for students to interact with video-based content and using alternate resources, such as Sway presentations, could potentially increase active learning on the "information and ideas" dimension of the ICD framework and thereby the popularity of these resources among students. Another interesting avenue is apps-based learning, which has been successfully trialed for the delivery of spectroscopy content,[43,44] albeit at a level of detail greater than required in the context of this course.

The activity on microplastic pollution was also well-received with an average rating of 9.1 and 59% of the respondents rating it a perfect 10; however, this evaluation is slightly less favorable compared to lectures and tutorials (Figure 4) and is most likely caused by the dislike for group work (Figure 6). This was a cohort comprised of students from diverse backgrounds, technical and otherwise. Furthermore, with the course being run in the first semester of the academic year, students would have had less time to establish a sense of community. While these circumstances are beyond the control of the instructor, they need to be built into the "situational factors" database of the ICD framework for improved course design.

Most of the group work in the microplastics exercise took place during the flipped class, when students discussed the article within their groups. Providing alternate opportunities for group work in the lead up to the session, such as preparing a summary sheet (nonverbal task), could help establish greater group rapport and be more inclusive for students less comfortable in contributing to oral discussions. Furthermore, during in-class discussions, students could be assigned specific group roles to facilitate a more organized discussion. While the ability to work collaboratively is not a listed course LO (Table 1), creating an environment that fosters this ability is key to improving student satisfaction and their eventual progress to being well-rounded graduates.

Taken together with the earlier finding of the low popularity of video recordings, an avenue worth exploring is digital learning resources that embed more opportunities for social interaction. While the ICD framework was used for a blend of "synchronous on-site" and "asynchronous remote" activities herein, the emerging trend of "synchronous blended" learning,[45] could also be considered by educators wanting to adopt this content within their teaching.

■ STUDENT PERFORMANCE

Student uptake of the three optional formative assessments was 67%, 71%, and 54%. Figure 7 shows the distribution of student marks in the three formative tests. The summative MCQs were designed to address the "comprehension" and "application" levels of the Bloom's taxonomy[29] (Table 1). The class average in the closed-book MCQ assessment was 50%, which is comfortably lower than that of the formative tests. As delineated in the "Final Design Phase" section, the MCQ test was held immediately after the conclusion of the spectroscopy section of the course. This left students with limited time to revise, potentially influencing the assessment performance. However, the decision to have such a close-on-the-heels assessment was made to harness the benefits of spaced repetition learning for the lab report due to be submitted a week later and the open-book OTLA to be held nearly two months after the MCQ test.[37] With this larger picture in mind, the closed-book MCQ was designed to be a low-stakes summative assessment (vide supra).

A favorable shift in the distribution of student scores is observed on going from the closed-book MCQ test to the OTLA (Figure 7) despite assessing for higher level outcomes in the

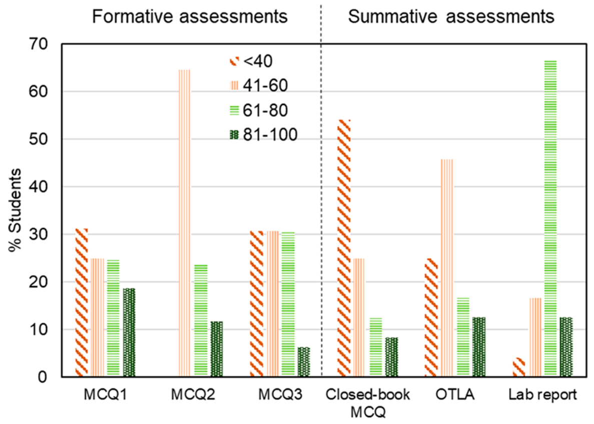

Figure 7. Distribution of student marks in the formative and summative assessments of the course. For the OTLA, the student marks shown are only for the spectroscopy section of the assessment.

latter (Table 1). Likewise, the average class performance in the lab report coursework is also impressive. Since open-book assessments more closely resemble real-life challenges that graduating students would go on to encounter, the improved student performance in these modes of assessment is particularly noteworthy. Interestingly, this trend of improved performance was also recently reported in dental education where a similar assessment model comprising closed and open-book exams was trialed.[46] Hence, the summative MCQ test can be envisioned as a stepping stone to success in the open-book assessments; discussing the solutions to the summative MCQs straight after the test is expected to have helped students bridge competence gaps ahead of the other summative assessments. Importantly, the student performance data validate the use of a spaced repetition-based assessment approach within the ICD framework.

■ CONCLUSIONS

The Integrated Course Design framework was used for the development of a course aimed at integrating a core analytical chemistry topic (spectroscopy) in a subarea of green chemistry (pollution analysis). Such courses assume importance amidst the growing emphasis on the nexus between chemical sciences education and education for sustainable development.

All components of the ICD framework—situational factors, learning objectives, assessment procedures, and learning activities—were explored for a course on spectroscopic methods for pollution analysis. The formulated learning outcomes addressed different cognitive levels of learning—evidence in the choice of action verbs: “describe”, “apply”, and “develop”. A multifold summative assessment model (MCQ, lab report, and OTLA) grounded in the principle of spaced repetition learning was designed to evaluate student attainment of the different LOs at different time points in the course. A combination of lectures, tutorials, lab sessions, and digital resources were used to design and deliver diverse teaching and learning activities covering a broad range of applications—from heavy metal contamination of water and lead pollution in soil to vehicle exhaust emissions and microplastic pollution—using the spectroscopy toolbox. Furthermore, these activities incorporated elements of active learning, problem-based learning, and flipped classes, where appropriate.

The timeline of the course was designed to promote the thinking of commonalities and the integration of different spectroscopic methods. In addition, a literature analysis activity on microplastic pollution was designed for students to pull together the knowledge they had acquired on the course and engage in reflective and critical thinking. In an endeavor to embrace the principle of authentic assessments, open-book assessments were assigned greater weight compared to the closed-book MCQ.

Student feedback surveys and student assessment performance were used as the two tools for course evaluation. Student feedback reveals a high degree of satisfaction on the fronts of course organization and quality of teaching and learning activities, thereby validating the use of the ICD framework for course design. There were two sources of relatively minor discontent: video recordings for asynchronous learning and group work as part of the literature analysis activity. While students had no issues with the quality of these educational resources, this feedback helped identify important lessons for how these modes of learning could be improved going forward. On student assessment, a sequence of summative closed-book MCQ quiz followed by open-book descriptive summative assessments was trialed. While spaced repetition was the pedagogical basis for the assessment model, student performance crucially shows a favorable shift in the distribution of marks on going from the closed-book test to the summative open-book assessment that targets higher order learning outcomes.

In closing, this article described the design, implementation, and evaluation of a course on spectroscopic techniques for pollution analysis to a postgraduate student cohort. Since the designed course starts with the underpinning principles of spectroscopy, much of the content could be adapted for delivery at the undergraduate level. In terms of scaling to larger sizes of undergraduate classes, most of the activities discussed herein are robust, with the exception of lab practicals that carry a direct time and space availability dependence. However, this is where recent advances in virtual lab experiences cited herein would be helpful. Most importantly, the translation of this course to an undergraduate program requires embracing the same attitude of change that has been prompted by green chemistry values. An open-minded approach to embed and integrate pollution analysis in existing spectroscopy or analytical chemistry courses is paramount.

■ ASSOCIATED CONTENT

SI Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.3c00705.

> Breakdown of student engagement hours, research-led teaching of spectroscopy applications for pollution analysis, examples of active-learning activities used in lectures, lab practical on spectroscopy methods for pollution analysis, example of problem-based learning in tutorials, summary of journal articles for flipped class activity on microplastic pollution and formative MCQs offered on the course (PDF) (DOCX)

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Notes

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