Adapting an inquiry-based approach for undergraduate chemistry laboratory courses: an exploratory study

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The exploratory study presented here is regarding the implementation of an inquiry-based instructional module developed for undergraduate chemistry laboratory courses. The study aims at understanding the challenges in execution of such a module and suggest ways for its effective implementation. It is important to bring changes in the present conventional practices to develop students as independent investigators and for learning experiences that are inquiry-driven, discussion-based and flexible as recommended by the NEP 2020. Based on this study, we suggest that the transition to inquiry approaches should be gradual. Further, students need adequate scaffolding of the learning process to help them in such a transition.

Keywords: Exploratory study, inquiry-based module, learning process, undergraduate chemistry laboratory courses, vitamin C.

CHEMISTRY Education Research (CER) has been providing valuable insights on alternative instructional approaches to restructure undergraduate (UG) laboratory courses[1]. However, large-scale instructional reforms for chemistry laboratory education at the UG level are challenging in the Indian context as infrastructure and available resources vary significantly across institutions. Nevertheless, it is important to bring changes in the conventional practices to develop students as independent investigators in the experimental domain.

Chemistry laboratory education is central to the three-year UG programme in colleges in India. On an average, students spend about 5–7 h per week in the chemistry laboratory during the first and second years, and about 13 h every week during the final year. Laboratory work carries substantial weightage (20–30% of the total marks) and this is justified as chemistry is an experimental science.

In conventional laboratories, often, students work individually and algorithmically following the procedure given in the manual to get the correct end result. Such instructional approach offers little challenge and opportunity to engage students in higher-order thinking skills, e.g. critical thinking, decision-making, etc.[2]. Further, it is important for students to understand the laboratory techniques and develop troubleshooting skills.

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CER has suggested various alternative approaches to laboratory education, e.g. discovery learning, problem-based learning, process-oriented guided inquiry learning (POGIL), etc. Table 1 provides a comparison of some of these alternative instructional approaches for UG chemistry laboratory courses.

In discovery learning, prior knowledge is often seen not as a necessity and during the process of exploration, there are equal chances that a concept may or may not be discovered[3]. Open inquiry complies with authentic scientific practice, but its pedagogical viability is not clear as the instructor does not have control over the direction of flow of the investigation. It may be difficult to execute in a large class and resource-constrained environment. The POGIL approach is possible with experiments which can generate rich data and students learn concepts through an inductive–deductive cycle. In the problem-based learning method, a context-based real-life problem is presented to students, which acts as a vehicle for learning a new concept through self-directed approach. Inquiry-based approaches provide minimal guidance to give students an opportunity to explore concepts by themselves; however, it is sometimes criticized for inadequate guidance[4]. These alternative approaches have recommended collaborative learning in the laboratory to help students.

Inquiry-based approaches provide opportunities to students to identify their knowledge gaps, reflect on the observations and interpret the data. Nevertheless, the conventional approach still predominates in most of the UG colleges affiliated to universities in India. Thus, it is essential to share feasibility studies of alternative approaches in the Indian context.

Table 1. Different instructional approaches for chemistry laboratory education

Instructional approach	Advantages	Disadvantages
Discovery	Motivational to students	Pedagogically challenging; ignores the need for prior knowledge.
Problem-based learning	Concepts strengthened through application in new context	Time-consuming
POGIL	Complies with nature and strategies of learning	May not be applicable for all kinds of laboratory experiments
Open inquiry	Complies with authentic scientific practice	Process versus content tussle

POGIL, Process oriented guided inquiry learning.

Table 2. Task grid for the titrimetric estimation of vitamin-C

Vitamin-C sample	Method-1 (redox)	Method-2 (acid–base)	Method-3 (redox)
Sample-1 (no chemically interfering component)	S/NS	S/NS	S/NS
Sample-2 (with one chemically interfering component)	S/NS	S/NS	S/NS
Sample-3 (multiple chemically interfering components)	S/NS	S/NS	S/NS

S, Suitable; NS, Not suitable.

In this article, we present our experiences related to implementation of an inquiry-based approach in a chemistry laboratory. The objectives of the study were to understand the following: (a) The feasibility of implementation of inquiry-based experimental module in UG chemistry laboratory. (b) The students' perception of the inquiry module.

Design of the module

The module was designed for the titrimetric estimation of vitamin-C in samples such as tablets and juice powder available in the local market. We chose vitamin-C because it is a familiar substance to students, easily available in the market and has well-established laboratory estimation techniques. Vitamin-C can be estimated by a redox titration (either using KIO_3, $FeCl_3$ or DCIP), or by an acid–base titration.

Students had to carry out redox and acid–base titrimetric estimation of vitamin-C in the given three samples and comment on the suitability of a particular method for a particular sample. The key idea was to draw students' attention to the components (other than vitamin-C) that may interfere with the estimation. Thus, students had to predict the interferences a priori and/or reason them post facto using the data. The objective of the task was to complete the following grid by pooling the classroom data (Table 2), and present appropriate rationale for the conclusion.

The module had pre-lab, lab and post-lab components. The introduction section of the pre-lab task-sheet presented the context of vitamin-C and the chemical information needed to carry out the work. The information included basic principles related to the estimation of vitamin-C by (a) redox titration using KIO_3, (b) acid–base titration using NaOH and (c) redox titration using $FeCl_3$. However, the procedural details of these methods were avoided in contrast to the manner in which they are given in the laboratory manual. Students had to design the experiment by choosing the samples, methods, concentration and the amount of chemicals.

We provided lab task-sheets with pointers and space for constructing an observation table for recording the titration readings and for calculation of vitamin-C content. The post-lab task-sheet contained space to record the students' interpretation, difficulties faced, etc. Table 3 presents the learning objectives of the task.

Since the task involved only acid–base and redox titrations, basic infrastructure of the laboratory and available chemicals in a UG laboratory were sufficient for this inquiry task.

Implementation of the module

The module was tested with two groups of first-year UG students. Study-1 (n = 12) was with a group of students who were invited for a winter workshop at Homi Bhabha Centre for Science Education, Tata Institute of Fundamental Research, Mumbai. These students were from different colleges across India. Study-2 was carried out with students from colleges in Mumbai (n = 32).

Students carried out the task as a small-group (three students in each group), and the time allocated was four sessions of 3 h each spread over two days. One of the authors acted as the facilitator in both these studies.

During the pre-lab session, students had to discuss and choose any two vitamin-C samples from the given three samples and two methods for titrimetric analysis from the given three methods. Students were expected to provide reason(s) for their choices. They had to write the

Table 3. Learning objectives of the module

Description	Learning objective
Content-related	Presence of other components in the sample is an important factor while choosing an appropriate method of quantitative estimation of the main component (vitamin-C)
Process-related	To design the experiment To apply prior knowledge in a new situation
Procedure -related	To acquire laboratory skills related to titrations

Table 4. Students' attempt to write chemical equations for titration involving KIO_3

$KIO_3 + KI + HCl \rightarrow I_2 + K_2O + O_2$
$KIO_3 + 5KI + 6HCl \rightarrow 3I_2 + 6KCl + 3H_2O$
$3KIO_3 + 3KI + 3HCl \rightarrow 3KOH + 3KCl + 3I_2 + 3O_2$
$KIO_3 + KI + HCl \rightarrow KCl + KOH + I_2 + H_2O$
$KIO_3 + K + 2HCl \rightarrow KCl + H_2O + I_2 + O_2$

appropriate balanced chemical reactions, identify stoichiometry and calculate the amount of sample to be weighed for preparation of the solution for analysis. The constraint imposed was that the titre value should fall between 10 and 15 ml. After providing enough time for this exercise (about 1 h), the facilitator collectively discussed the calculations with the class to provide opportunity for corrections, if any.

In the laboratory, students prepared sample solutions according to their molar calculations, and performed titrations using the methods chosen by them. The procedures for the titrations were generated by them through discussion or consulting an on-line resource. However, the chemical concentration, amount, volume, etc. had to be chosen through decision-making because of the imposed constraint of the titre value (which again could be chosen by the students from the range 10 to 15 ml as mentioned earlier).

During post-lab work, they shared their results with different small groups to collate and reflect on the larger data. Collaborative learning was a part of the experience throughout.

Changes in the module after the first study

While conducting the trials in the laboratory, students faced the following difficulties. Accordingly, we made some changes in the module. These include:

- The titration with ferric chloride was discarded as students found it difficult to maintain 60°C during titration. Students of study-2 had to carry out acid–base and iodometric titrations.
- One of the vitamin-C samples posed difficulty in the detection of the end-point due to the inherent orange colour of the sample. This sample was replaced by the white-coloured vitamin-C sample.
- During our first trial, students had to analyse two samples using two methods. We noticed that the students were struggling to finish the lab-work within the stipulated duration and had to be given extra time. To understand whether reduction in the number of samples would help students save time, we reduced the number of samples from two to one during the second study.
- Students did not have a reference sample for comparison and assumed errors to be personal. As a choice we gave vitamin-C sample (tablet) containing only ascorbic acid and no chemically interfering substances as a reference sample during the second study.

The space provided for drawing the data table in the lab task-sheet was not best utilized by the students. The following changes were introduced in the lab task-sheet:

- The hydrogens in the chemical formula of vitamin-C were marked 1 and 2 for identification of carbon atom undergoing deprotonation.
- Take-home assignment based on the molar calculation was given to help students recall the steps involved in the molar calculations.
- The observation table for recording the readings was introduced in the task-sheet.
- A table for compilation of results was introduced in the task-sheet to help in the interpretation of the results.

Results and discussion

Planning the task

During pre-lab, writing balanced chemical equations for the titration reactions was challenging for the students. Some students of study-1 could access the internet to write the correct balanced chemical equations. However, in study-2 the internet was not accessible to students and we observed that they wrote multiple alternatives for the reactions (Table 4). They discussed the reactions written, and accepted or rejected the alternatives; for example, they rejected reactions that could not be balanced or showed evolution of O_2 (which was not stated as a product in the information provided). Such a discussion provides better learning opportunities than direct access to information from the internet. Table 4 presents students' attempt to write molecular equations. Possibly a prompt in the task-sheet may help draw students' attention to the entities involved in the redox half-reactions; thereby possible mistakes could be avoided. It was easy for students to write the chemical equation between ascorbic acid and iodine because the molecular formula of dehydroascorbic acid was given in the introduction section of the pre-lab task-sheet, suggesting the stoichiometry.

For acid–base reaction, students had to ponder over the likely balanced chemical equation and the stoichiometry between sodium hydroxide and ascorbic acid. They were unsure of which hydrogen atom(s), indicated by the numbers 1 and 2 in Figure 1, would be replaced. This dilemma provided the opportunity for discussion, as arriving at the correct stoichiometry was important for the amount of sample required for preparation of the solution. Here students had to connect the theory with practice (titration). Thus, vitamin C poses an interesting titration problem.

The other difficulty was with respect to calculations involving mole concept. Students in both studies found molar calculations difficult.

The challenges were in:

- Correct use of molar ratio for determining the mass of ascorbic acid.
- Use of the following two equations together for estimating the amount of vitamin-C sample needed.

  Number of moles = MV,

  $$\text{Number of moles} = \frac{w}{\text{Molar mass}},$$

  where M is the molarity, V the volume (l) and w is the weighed mass.

- To consider the amount of vitamin-C sample in the total stock solution rather than the volume needed for titration.

Often, as a part of the experimental procedure, students are provided with the chemical equations and formulae for calculations. Instead, we could provide them the opportunity to do these molar calculations on their own and reflect on the errors. This may help in sustained learning for application in a new situation.

Laboratory work

During the pre-lab work, students did not notice chemically interfering substances present in the composition of vitamin-C sample. They performed the laboratory work with confidence because titration is a familiar task. When they encountered problems due to chemical interference, it was puzzling for them since they could not a priori reason it. The puzzling result allowed the students to ponder over what might have gone wrong. Day-1 was a little disappointing for the students, but a change in their outlook was noticed on day-2. In fact, the puzzling result drew greater attention to the task. They became more careful and serious about the laboratory work; some students stated the same in their interviews/feedback. Many of them carried out the titrations again to ensure that the errors were not due to procedural negligence or personal mistakes.

For the given task, students had some freedom to extend the investigation. In an instance, a group of students tried to dissolve vitamin-C tablet by heating, assuming that the solubility increases with temperature; but their attempt was in vain. They did not consider the possibility of substances (binders) in the tablet that may be insoluble in water. Such instances can be taken for discussion in the post-lab session and the interactions become rewarding because these substances may not interfere chemically, but may affect the strength of the solution. Thus, titration of market samples of vitamin-C gives exposure close to a true investigation.

Since students are in the phase of learning, we cannot expect perfect laboratory skills and thus the facilitator needs to interact with them. A possible alternative is to show videos on titration techniques before they start the laboratory work.

Collation of data

The post-lab task required students to collect and collate data from all the other students. The post-lab discussion session is, therefore, a vital component of the collaborative learning because all groups do not try all the combinations. To facilitate the post-laboratory work as well, students were asked to construct the data table on the black board/whiteboard. Each group entered the data collected by them during the laboratory work and this was followed by discussions.

We observed that some students were uncomfortable in accepting a flaw in the values obtained by them. The facilitator had to emphasize that the data belong to all the

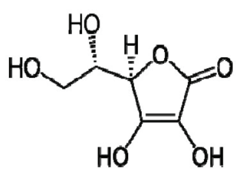

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Figure 1. Structure of ascorbic acid, vitamin-C.

Table 5. Qualitative account of students' responses in the feedback form

Descriptor	Prototypical responses
Interaction with peers	We got the opportunity to know Our mistakes Other's opinions and ways of thinking Problems faced by others and comparing them with our own experiences Pew friends
Strength of the module	We did not Blindly follow the instructions from the book Put one value and calculate from previous given data We got to Study the actual concept related to the experiment Improve our skills and thinking
Weakness of the module	It may be difficult if students Did not know how to start the experiment Are introverts; then discussion may be difficult Think it is lengthy or boring
Interesting part	Deviation in the result of practical from theoretical values Calculations (stated by 15 students) Experimental work (stated by 22 students) Knowing our capability to solve the problem Using familiar sample for estimation
Boring part	Calculations (stated by 16 students) Nothing (stated by 12 students)

groups for interpretation, and students need to jointly and carefully accept/reject data points for holistic interpretation.

They arrived at the conclusion that acid–base and iodometry titrations are suitable for the first sample which did not contain any chemically interfering substances, whereas iodometry is better for the second sample with sodium ascorbate as an interfering substance. Both the iodometry and acid–base titrations are not suitable for the third sample which had reducing agents.

Students' perception of the module

One of the objectives of this study was to capture students' impressions about the module. They were asked about the strength and weakness, as well as the interesting and boring parts of the module. Their perceptions about the collaborative work were also captured through a question in the feedback form. Table 5 provides a qualitative account of the results from 42 students in both the studies.

These responses indicate that the students received support from their peers for understanding and completing the challenging task. The calculations were considered to be boring by as many students as those who found it interesting. Further study may be required to understand the reason behind such opposing response related to calculations.

Analysis of the lab task-sheet indicates that about 21 out of 42 students chose to analyse juice powder. Almost all of them provided the reason that they would like to know about the energy drink used in day-to-day life. Most of them were curious to know about this sample, perhaps, because it offered a familiar context. This supports the design point that a familiar context could motivate a student to learn.

Focus-group interview with the students of study-1 indicated that their experience with the module was quite unlike what they had come across in their college laboratories, where they were spoon-fed with no independence in the work environment. Students considered that the most important learning was the opportunity to reflect on the errors. Some of them also stated that the actual learning took place while they were discussing to collate the data for presentation. These impressions suggest that we need to seriously rethink the current practice followed in experimental work in UG colleges.

Suggestions for effective implementation

The inquiry module implemented in our exploratory study gave students the freedom to choose two samples and two methods out of the three samples and three methods provided. It is motivating to students as they get to decide what they want to investigate. Pure ascorbic acid LR-grade sample which acts as reference can be provided as one of the samples.

In a conventional laboratory course, students generally record only the titre value in a titrimetric experiment. We suggest that the lab task-sheets should contain prompts which present cues to students to record various qualitative and quantitative observations. With such cues, they can start observing carefully any noticeable change in the system that they work with. Introduction to pre-lab is equally important to prepare students for the task and the post-lab to focus on data evaluation for drawing the conclusions.

It is important that students should not find the given task too frustrating as they are likely to be discouraged. It is essential to conduct discussion with the entire class by posing questions that may act as a scaffold to help students think and reflect. The instructors who take up the role of a facilitator, should not provide answers or give suggestive or directional cues. The facilitator needs to be careful to prevent digressions in discussion and navigate towards the desired outcomes. Effective implementation of such inquiry modules is possible with such orientation of the facilitators.

Conclusion

The module on vitamin-C in the present study provided multiple learning opportunities to students such as to: (a) revisit concepts of molar calculations and apply them in the given context; (b) plan the appropriate procedural details and execute the plan in the laboratory; (c) collate and compare the class data; (d) arrive at data-based inference and (e) engage with soft skills like teamwork and communication.

Students successfully completed the task despite the challenges faced, which actually offered opportunities for learning. The feedback by students suggested that they enjoyed the task and appreciated the freedom given to them to choose the samples and methods.

We structured the module based on our belief that shift to inquiry-based laboratory approach needs to be gradual for students from conventional laboratory set-up who are at the zeroth level of inquiry[5]. We agree with Scott and Pentecost[6] that integration of moderate level of inquiry increases the difficulty level, and our observations in this study indicate the same. Thus, in our opinion, the transition to higher levels of inquiry may be feasible in an incremental manner, i.e. a stepwise transition from structured inquiry to guided inquiry followed by open inquiry.

Based on the exploratory study, we understand that there is a definite scope to introduce such approaches in laboratory settings of colleges in India. Further, class size in the laboratory work does not appear to be a major constraint for implementation. It is important to implement such cognitively demanding activities as collaborative work. The additional advantage of group work is that it allows sharing of equipment.

It is important to develop such modules for chemistry laboratories in the Indian context and share the implementation experiences to provide useful insights to educators. We recognize the need for a change of teachers' role to that of facilitators while implementing inquiry-based modules. The teacher professional development programmes in higher education need to consider such aspects. Also, continuous engagement with inquiry tasks is important for a deeper understanding of the experimental domain.

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