Rethinking science and mathematics pedagogy in Indian higher education

Aahana Ganguly, Divya Uma, Proteep Mallik, Sravanti Uppaluri and Tulsi Srinivasan*

Undergraduate science and mathematics curricula in India are still mostly centred around content, and the pedagogy on delivering this content. This does not serve the needs of a diverse student body, nor the needs of these disciplines. Keeping in mind the multiple constraints that undergraduate teachers face, we provide some pedagogical principles for student-centred learning, and some examples illustrating these principles that we believe can be carried out in different contexts.

Keywords: Interdisciplinarity, local context, science education, self-directed learning, undergraduate pedagogy.

THE approach to undergraduate (UG) science and mathematics education in India is largely a continuation of that from senior secondary school – it is content-heavy, emphasises rote memorisation, and presents the sciences as being somewhat siloed in nature. The focus is on acquiring procedural skills to solve a narrow set of problems. These practices have led to college students being unable to connect to what they are learning or to draw on their learning outside narrow forms of assessment.

We are seeing a steady increase in the number of students enrolling in higher education in India[1]. This happens against a complex backdrop of economic, social and environmental challenges. Students come with a range of experiences, aspirations and academic-preparedness, and educators and policymakers need to consider what the goals of UG science programmes should be, as well as how to design programmes that best serve the students who enrol in them.

As disciplines, science and mathematics are well-suited to meet this challenge. The practice of science and mathematics necessitates observing one's surroundings, working with one's hands, thinking critically and creatively, collaborating, including with people with different ideas or from various backgrounds, and communicating ideas. These disciplines will then become a fertile terrain for students to hone the skills and dispositions that will help them navigate a complicated world. The approach to science that is most meaningful for a student who will not continue in the discipline may also be the one that best trains students who wish to become researchers.

To translate this somewhat grandiose vision of science education to curricula, we need a holistic approach to the teaching–learning process, and an acknowledgement that learning requires active engagement from students[2,3], that learning is determined by a student's prior experiences and their interactions with the environment[4], and that 'facilitated discovery' is more effective than direct knowledge transfer. We also need to bear in mind the practical challenges of uneven language and mathematics skills, poorly equipped labs, and large classrooms.

Reflecting on the course design and pedagogy of our colleagues, we identified the following broad principles as informing much of our collective practice:

(1) Provide opportunities for students to make observations and formulate hypotheses: This may take the form of specific pedagogies like inquiry-based learning, or involve designing labs in which there is more freedom for students to pose questions, or class activities involving students coming up with hypotheses for a given phenomenon.

(2) Encourage group discussions and a sense of collective ownership over learning: This principle is something that guides nearly all our pedagogical practices, as we believe the ability to listen to other people's ideas, argue for one's claims, and respond to feedback in a respectful and inclusive atmosphere is key to doing good science, and also one of the most meaningful parts of learning in a university as opposed to on one's own. Again, this may be in the form of specific pedagogical practices but is also a principle that can be worked into any class through structured group activities and class discussions.

(3) Create a tinkering culture: By this we mean a broad culture in which students play around with materials or ideas to understand a concept or pose new questions. This could be facilitated in various ways – ensuring easy lab-access for students outside classes, building equipment from scratch using easily available material rather than using opaque lab kits, using computers to study examples of a mathematical definition or theorem, etc.

The authors are in the Azim Premji University, Bengaluru 562 125, India.
*For correspondence. (e-mail: proteep.mallik@apu.edu.in)

(4) Highlight local contexts: This could involve case studies relevant to a locality or include examples that students come across in their everyday lives.
(5) Provide students with an integrated view across disciplines: This involves emphasising the different lenses through which a phenomenon can be understood, within and beyond the sciences.

We are by no means the first to identify these principles, and several active-learning pedagogies are designed around various combinations of the principles above (2, 3 and 4). However, we believe that they provide some bridge between the learning goals and challenges articulated above, and that they can be incorporated into most Indian science classrooms realistically (Figure 1).

In the rest of this article, we provide illustrative examples of how these principles can be incorporated into courses. In each case, we also discuss specific skills that the example helps develop. Many of these skills are based on the transdisciplinary tools of inquiry, and capacities for mathematical and scientific thinking identified by Patwardhan *et al.*[5] and Mohanan and Mohanan[6], such as observation, categorisation, abstraction and generalisation, explaining and predicting, and articulating and debating. These skills are highlighted in the examples below.

Example 1: Plot observations in a biology course

Pedagogical principles: (1), (2) and (4)

Groups of students are assigned a piece of land in the neighbourhood. Over a semester, they observe, characterise, and quantify different aspects of microbes, plants, insects and birds. Students document the changes in the plot through journaling, making sketches of what they see, and asking questions based on their observations. Finally, students submit a written assessment where they propose a research question and an experimental design based on their plot observations.

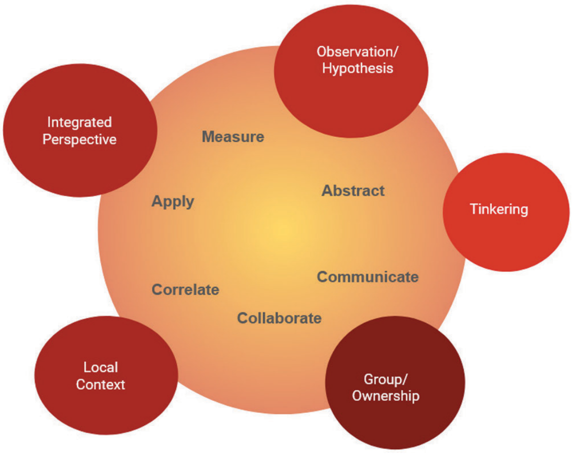

Figure 1. Diagrammatic representation of the pedagogical principles and how they help develop specific student capacities.

Students make natural history *observations* about plants and animals around them. They learn to notice big and small things, and changes occurring daily. Through *collective discussion* with faculty and peers, and online resources, they gather more information about the natural world around them. For example, one student group noticed some fly-like organisms were gathering on the same twig every evening. Upon taking pictures, and consulting with faculty, they identified them as blue-banded bees, and not flies (Figure 2 *a*). Students began to concentrate on this particular bee. On a different occasion, students observed a lynx spider near the bee aggregate (Figure 2 *b*). Students *asked why* the bees were aggregating and potentially making themselves more visible to predators. They came up with two potential *hypotheses*: the first is that it makes them look bigger, and the second is that aggregation helps them to stay warmer. These observations and ideas were *communicated* as journal entries and proposals.

Encouraging such enquiry, cultivates critical thinking, ownership and scientific temper in students. This creates a level playing field, as student background does not seem to determine creativity in generating questions.

Example 2: Structure-property-use relationships in polymers

Pedagogical principles: (1), (2), (3) and (4)

When learning about complex concepts such as polymer structures and their modification for different uses, students are asked to dissect everyday materials like diapers (instead of observing polymer samples taken from commercial chemical bottles in a chemistry lab), and study the super-absorbing properties. They are asked to connect their observations with the structure of sodium polyacrylate and to develop a mechanistic hypothesis to explain superabsorption.

Students *systematically identify* the diaper with the best superabsorption capacity from various brands of diapers. They *observe* the structure of a diaper and dissect it to

Figure 2. Research question/proposal generated through plot observation. ***a***, Blue-banded bee aggregate observed near Azim Premji University (old campus), Bengaluru. ***b***, Lynx spider (highlighted in red oval) preying on the bee. Photo credit: Prerana Waran.

identify the substance responsible for super absorption, and to isolate polymer powder. Students study the absorption capacity of the polymer quantitatively using water and salt solutions. Knowing the structure of sodium polyacrylate, students *hypothesise* that the structure of sodium polyacrylate is responsible for its super absorbent properties. Based on the data collected for water and salt solutions, students are able to *propose* a mechanism for super-absorption based on osmosis.

Example 3: Discovering graphs

Pedagogical principles: (1) and (2)

Students are provided with a selection of problems of varying difficulty that can be solved using graphs. For example, can a particular shape be traced without lifting one's pen from the paper or going over a line again? Can a total count of all 'friends' of all people on a social media app result in an odd number? Or some version of the three utility problem (in Bangalore, this can be posed as a question about elevated corridors joining various points). As they work through the problems, ideally in groups, they automatically start to draw graphs and to make hypotheses in the language of graphs. Following this, perhaps the next day, a formal definition of graphs is given by the instructor (with inputs from the students), and students are asked to return to the problems, try and state them in the language of graph theory, and see if they can answer any more questions.

An exercise of this sort can be the beginning of a course in graph theory or combinatorics that uses inquiry-based learning, or an introductory course on proofs. Typically, once graphs and the degree of a vertex are formally defined, it becomes easier to prove given statements and *formulate hypotheses*. Students may observe that, perhaps counterintuitively, it is sometimes easier to provide proof in an abstract context, where there are no distracting or misleading details.

This exercise is especially useful to illustrate for students starting college that, more than solving equations, mathematics is about *observing patterns*, *making hypotheses* and *arguing* for them. Through carefully arranged group work or a moderated discussion, the value of *collaborative thinking* in mathematics can also be experienced by students. This value is partly intellectual (articulating ideas can help sharpen them and discussions can lead to spotting errors) and partly social (thinking through a problem together can bring people together).

Example 4: Thermal properties of carbon dioxide as a greenhouse gas

Pedagogical principles: (1), (3) and (5)

For many phenomena ranging from the simple (thermal properties of carbon dioxide) to the complex (thermohaline currents), simple science experiments with common chemicals and equipment are much more effective than a textbook technical explanation. There are several examples of simple demonstrations of climate phenomena which are easy to understand and replicate in a classroom environment. For example, the thermal properties of carbon dioxide as a greenhouse gas can be demonstrated using two conical flasks or bottles under a hot lamp or in sunlight, vinegar and baking soda and, two thermometers.

Students are able to *observe and measure* the temperature change in a 'mini-greenhouse' directly and contrast the temperature change in an atmosphere with air and an atmosphere with a very high concentration of carbon dioxide. Students *tinker* with the experimental setup to make the best demonstration of the greenhouse effect possible. They experiment with different ratios of sodium bicarbonate and water to produce carbon dioxide in the flasks. They experiment with the best way to seal the flasks and measure temperature (thermometer or IR thermometer) and also experiment to decide on the best heat source to emulate the Sun.

Example 5: Impacts of climate change

Pedagogical principles: (1), (2), (4) and (5)

Nowhere is the need for an interdisciplinary and integrated approach to education more visible than in a climate science classroom[7,8]. The study of climate change has to involve the study of humans as an agent of planetary change. To broaden the scope from an exclusive focus on science in climate studies, gamification has proved to be a useful way of simplifying interactions between socio-economic factors and the environment and developing a capacity in students to take action.

For example, understanding agricultural challenges of altered climatic patterns on a societal level is difficult for students but during a game where students role-play as farmers making decisions on crop-planting, they are able to strategise and effectively perceive the complex effects of climate change on agriculture. The agriculture game played in class follows a discussion on the effect of planetary and local climatic changes on agriculture. Students role-play as farmers given a fixed amount of capital (in the form of tokens) to invest. Students decide whether to invest in flood resilience, drought resilience, cyclone resilience or nothing if they anticipate no extreme weather events. The weather outcome is then decided by a random number generator or, in a simpler version, a die. Farmers then make losses or gains depending on the outcome. Farmers who run out of tokens (capital), become bankrupt and have to leave the game. The aim of the game is to not become bankrupt. In such games, students can *correlate* concepts learnt in lectures with a simplified real-world problem such as farmers facing different rainfall outcomes decided by the

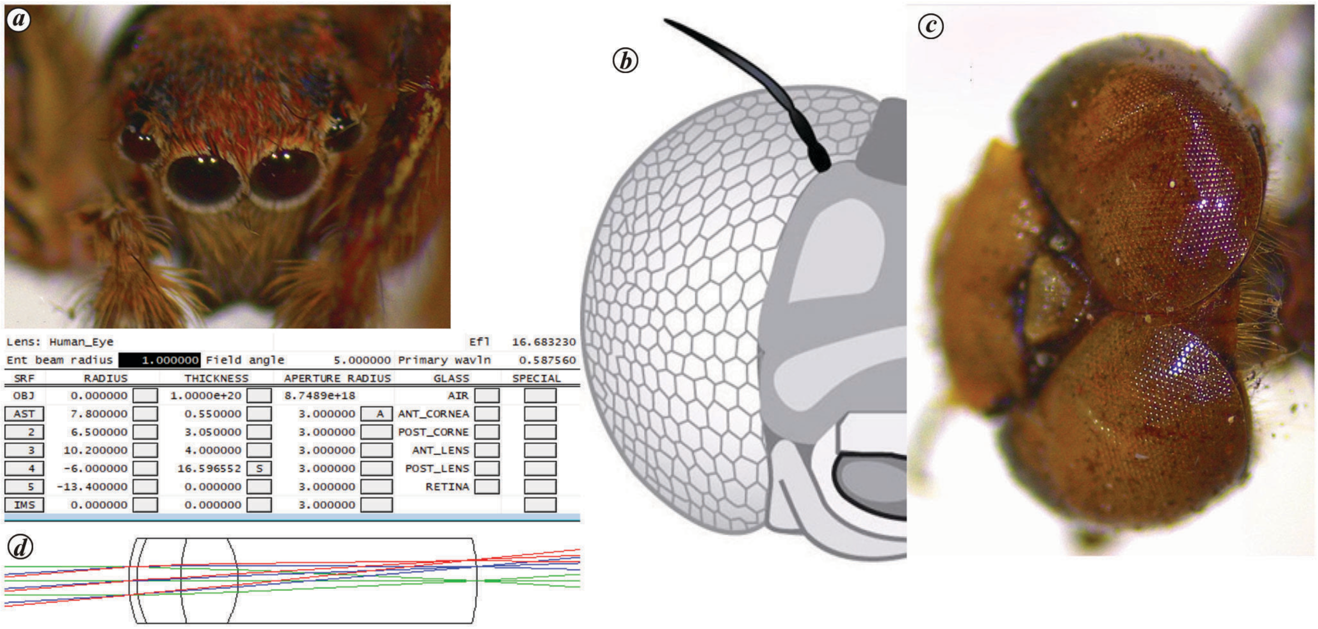

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Figure 3. An integrated vision – studying animal and human vision. ***a***, Simple eyes of a jumping spider; ***b***, schematic of compound eyes in an insect, such as that of a dragonfly seen through a microscope as shown in ***c***. ***d***, Modelling human vision using the computer using OSLO-EDU.

role of a die. They have to *collaboratively* make decisions on investments in resilient crops as a group to survive.

Example 6: Integrated vision

Pedagogical principles: (1), (2) and (5)

Research in the sciences in the modern world cannot be siloed into narrow disciplines and science education should reflect this new interdisciplinary reality. All UG science programmes must integrate content from other sciences so that students can apply concepts they learn in physics or chemistry, for example, to the study of organisms in biology. Integrating content with an understanding of the societal and environmental effects outside the sciences enables students to understand the broader implications of the content they learn[7]. An example is the study of the animal eye which encompasses physiology, neurology, chemistry and physics. We have designed a comprehensive lab module for the fourth-semester optics course where students use microscopes to observe insects eyes and make measurements to help model the insect eye on a computer (Figure 3).

Students *observe* how a jumping spider, which has several simple eyes (Figure 3 *a*), kept in a small chamber along with its prey, say a fly, goes about catching the fly. Students are also shown videos of various insects, such as the praying mantis, which has compound eyes, and they observe how they catch their prey. By measuring the geometric parameters of the compound eye (Figure 3 *b*) of an insect with the aid of a microscope (Figure 3 *c*), students then model the eye on the computer and *analyse* its optical performance (Figure 3 *d*). This helps them understand concepts around imaging and how the brain compensates for the various aberrations inherent in the imaging system. Some of the *questions* students grapple with include – why do some animals have simple or compound eyes? What about colour versus black-and-white vision? Are the reasons evolutionary or are they adaptations specific to their environments? These and many other questions naturally arise from observations and analyses that the students do. Further, optical illusions are used to understand how human vision works, which is an interplay of the optics of the eye and the processing of the human brain. Finally, students gain knowledge about vision in broader and more *abstract* terms and study on their own the role of optics, chemicals, electrical signalling, and image processing in animal vision. They are now prepared to *apply* their knowledge to address vision impairments, such as how retinal implants are currently used to cure blindness.

Example 7: Making physics transparent

Pedagogic principles: (1), (2), (3) and (4)

UG physics has not changed much in many decades. Much of the development of physics over the last hundred years builds upon the theories and experiments of Kepler, Newton, Galileo, Faraday and others. This often results in curricula and teaching methods that are ossified and lack ingenuity.

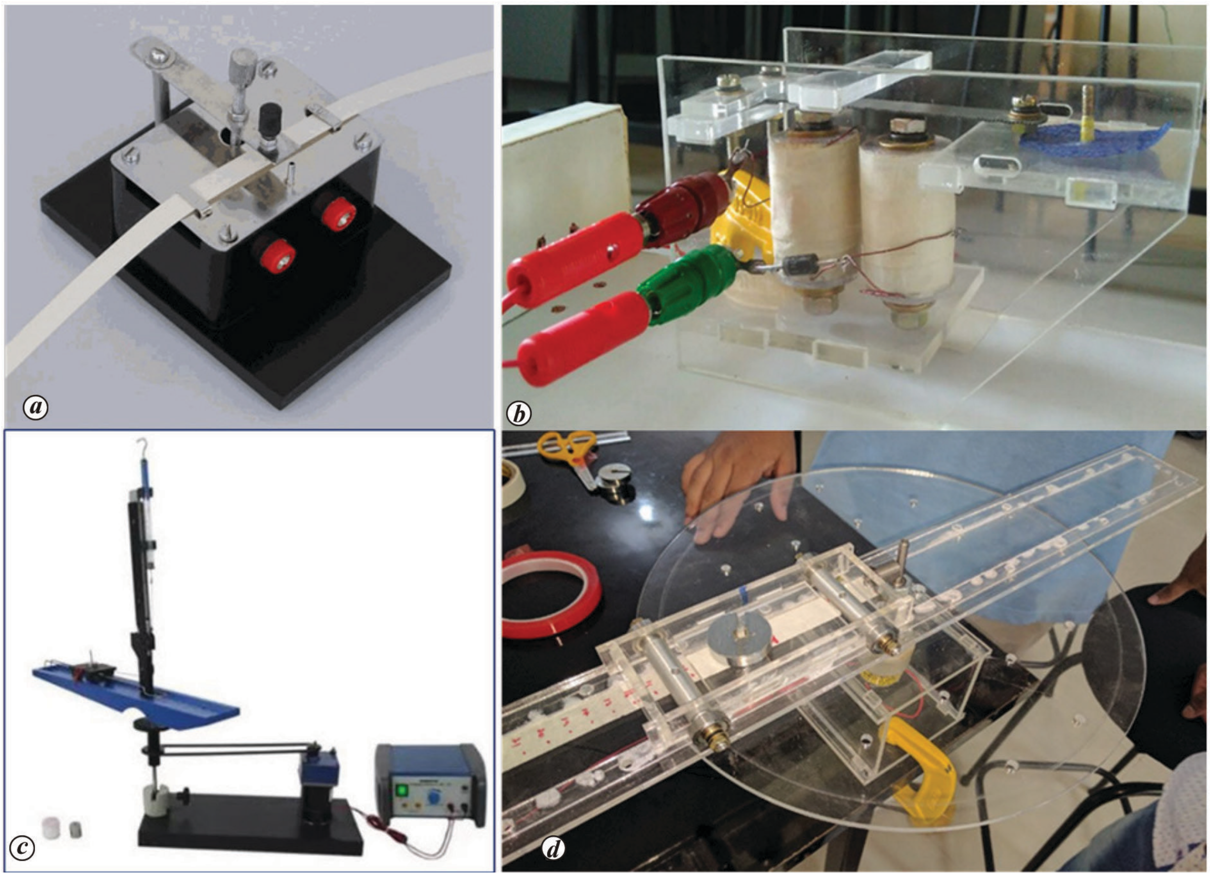

Figure 4. ***a***, Commercial ticker timer (MVTEX) used in kinematics experiments. ***b***, Ticker timer designed and built on our campus, where the constituent parts are visible to the students. ***c***, A commercial centripetal force (INDOSAW) setup used in physics labs. ***d***, The setup we have designed and built with a motorised rotation table and track to study forces. Our setup is simple, low-cost and easily fixed if it breaks.

Most of our physics courses have a strong experimental component. Physics labs typically require significant investments in purchasing equipment, consumables, and maintenance, capital expenses being the largest part of the pie. Re-designing experimental setups and building many of them from scratch in our labs has helped lower costs, make maintenance a simpler and in-house effort, and create an environment that fosters tinkering and creativity. Standard black-box kits, seen in almost all UG labs around the country, are largely absent from our labs. Our setups are often made of clear acrylic, making them transparent for students to see all the parts (Figure 4). Our maintenance costs are low since equipment can be repaired or rebuilt in-house. Students can closely observe the functioning of these setups, for example how power supplies, ticker timers, and DC motors look and work. This also helps foster an environment of curiosity and tinkering.

This approach was a significant advantage when the world was hit with the COVID pandemic and our institution like all others was forced to shut down and move all its courses to an online mode. We were able to continue a large part of our experimental curriculum by shipping simple parts to the homes of students. We purchased materials locally available at hardware stores and sent kits to students with instructions on how to conduct simpler versions of experiments in the course syllabus. Some of the materials students use are typically found in homes, such as recycled materials, kitchen supplies, etc. Students built their setups, performed experiments, analysed their data, and submitted videos along with their lab reports. Such low-cost, technology-assisted labs have been carried out during the pandemic in other countries as well[9]. This can be implemented even in regular times in under-resourced settings (colleges without labs, equipment, or specialised teachers).

The simple, transparent setups help students become mindful and *observant*, learning about different types of materials and what is suitable for specific purposes. Building lab setups from scratch leads students to do lab-based projects for their assessments. Simple setups make the experiments more *accessible* to students and they develop a desire for answering *questions* via experimentation. Students become very comfortable in the lab, using equipment of all kinds, and they develop fine motor skills. This translates to a willingness to *tinker*, build and repair all kinds of gadgets and equipment, which is an important life-skill. Using a ticker timer, for example, while doing a mechanics experiment, students learn how an electromagnet works to create the dots on the ticker tape. This helps break the compartmentalisation of physics topics in the student's mind and they can *apply* their learning to broad areas within the discipline.

Summary and conclusion

A collaborative culture is central to the practice of science. Universities may consider creating inclusive learning environments as an end-goal in itself, especially given the history of exclusion in educational spaces in India, but science itself becomes richer when the questions considered and methods used are not determined by a small group of people. For any of the techniques described above to be successful, students need to feel comfortable within the classroom and during peer interactions.

Labs – especially when students are given open-ended tasks that require some innovation, in-class group activities – and project work are opportunities for students to brainstorm together and draw on one another's strengths. However, due to a lack of supporting structure, existing social barriers and divisions may inhibit learning. The examples provided in this article demonstrate how essential learning dimensions can be incorporated into pedagogical practices. These must be followed up with rigorous and appropriate assessment practices.

How students leverage their UG training toward employment, or further higher education is extremely varied. Varied as it may be, our ultimate goal as educators is for our students to live in society as collaborative beings with the ability to think critically and be reflective in their actions.

1. Ministry of Education, All India Survey on Higher Education 2021–22, 2022; https://aishe.gov.in/aishe-final-report/.
2. Freeman, S., Eddy, S. L., McDonough, M., Smith, M. K., Okoroafor, N., Jordt, H. and Wenderoth, M. P., Active learning increases student performance in science, engineering, and mathematics. *Proc. Natl. Acad. Sci.*, 2014, **111**(23), 8410–8415.
3. Theobald, E. J., Hill, M. J., Tran, E., Agrawal, S., Arroyo, E. N., Behling, S. and Freeman, S., Active learning narrows achievement gaps for underrepresented students in undergraduate science, technology, engineering, and math. *Proc. Natl. Acad. Sci.*, 2020, **117**(12), 6476–6483.
4. King, D. and Ritchie, S. M., Learning science through real-world contexts. In *Second International Handbook of Science Education* (eds Fraser, B., Tobin, K. and McRobbie, C.), Springer, Dordrecht, 2012, vol. 24, pp. 69–79; https://doi.org/10.1007/978-1-4020-9041-7_6.
5. Patwardhan, B. *et al.*, Reimagining Assessment and Accreditation in Higher Education in India [White paper], National Assessment and Accreditation Council (NAAC), Bengaluru, 2022.
6. Mohanan, K. P. and Mohanan, T., Learning to think like a scientist and a mathematician. *Curr. Sci.*, 2018, **114**(3), 447–451.
7. McCright, A. M., O'shea, B. W., Sweeder, R. D., Urquhart, G. R. and Zeleke, A., Promoting interdisciplinarity through climate change education. *Nat. Clim. Change.*, 2013, **3**(8), 713–716.
8. Khan, M. S. and Wells, M. A., Integrating interdisciplinary education in materials science and engineering. *Nat. Rev. Mater.*, 2023, **8**(8), 491–493.
9. Abriata, L. A., How technologies assisted science learning at home during the COVID-19 pandemic. *DNA Cell Biol.*, 2022, **41**(1), 19–24.

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