*Research Article*

# Developing Science Teachers' Understanding of Engineering Design Process through Workshop on Biomimicry for Green Design

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## ABSTRACT

This study aims to examine the effect of a training workshop about design-based learning integrated with biomimicry for sustainability on science teachers' understanding of the engineering design process. Participants (N=30) were recruited from STEM high schools in the central part of Thailand. During the two-day intensive workshop, the participants attended a special lecture on biomimicry for product design and development, engaged in a design challenge, designed and presented lesson plans and obtained feedback, reflected on their workshop experience, and discussed possible challenges and issues in implementing design-based learning with biomimicry in their classroom contexts. The results indicate that most of the teachers already had a sound understanding of many essential features of the engineering design process. Nonetheless, the workshop could broaden and reinforce their knowledge. The participants learned the following during the workshop: a design challenge always has a problem; limitations need to be considered during the design process; innovators must work on prototypes and test and improve them before creating full-scale products; the design process is iterative and sometimes messy. Finally, implications on education for sustainable development and the development of $21^{st}$-century skills as well as some challenges and issues in school implementation are discussed.

**Keywords:** pedagogical knowledge, engineering design process, biomimicry, integrated STEM education

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## Introduction

Natural resources are being exploited and polluted by human activities tremendously. To sustain the world, the United Nations has launched, and is encouraging all nations to adopt, the Sustainable Development Goals (SDGs). This study gives an example of how the education sector could help address and solve the natural degradation crisis. This project developed a professional development program to equip science teachers with pedagogical knowledge for addressing and archiving two SDGs in their classrooms through design-based learning: goal 12 (efficiently managing our shared natural resources) and goal 15 (halting biodiversity loss, with focus on plants and forests). Design-based learning is based on inquiries but requires students to use design thinking and a design process to solve real-world problems. It is traditionally and usually employed in disciplines associated with design, such as art, architecture, and engineering; it can also be adopted in subject matters not normally considered to be design-related, such as science, technology, and business [1], as reconceptualized by many science curriculum frameworks, such as the US's Next Generation Science Standards [2], Thailand's revised science curriculum framework [3], and Thailand's national framework for STEM education [4]. Previous studies indicate the positive impact of design-based learning, wherein students design and create products or procedures, on many learning outcomes [1, 5-7]. These positive effects include enhanced cognitive and affective development; understanding and application of knowledge, and $21^{st}$-century skills-collaboration, communication, critical thinking, creative problem solving, motivation and interest, sense of ownership, and emotional intelligence. It also improves lower-achieving students' learning.

A literature review [8-12] shows that many science teachers value design-based teaching, but the implementation in their classroom contexts is limited by many factors, including pedagogical challenges, structural challenges, concern about students, concern about assessment, and lack of teacher support. According to the authors' preliminary interviews with some biology teachers, design-based learning is perceived irrelevant and impossible for biology classrooms. Such teachers feel incapable of dealing with the challenges involved in implementing design-based learning. They do not realize that they can use this approach to encourage students to apply their knowledge creatively to take action regarding biodiversity, conservation, and sustainability for the degrading environment. Fortunately, recent literature on biomimicry in design education sheds new light on the integration of biology-technology-engineering and mathematics (BTEM), an innovative framework for implementing the design process for sustainability in biology education [6,13]. Biomimicry takes nature, an established natural system, as a mentor and a rich source of inspiration through observing its time-tested models, systems, processes, and strategies in pursuit of sustainable product design and development.

This project aims to examine the effect of a workshop about design-based learning for biological sustainability on science teachers' understanding of the engineering design process. The workshop was designed to provide first-hand experience by engaging the participants in a conservation design challenge and providing teaching guidelines that will allow them to encourage their students to design and act for the threatened natural environment through the design process. We argue that teachers who aim to learn how to teach through integration need to experience STEM integration as learners [10]. They should either engage in disciplinary practices or learn in integrated ways; otherwise, they may find it exceedingly difficult to teach students using these ambitious methods.

## Literature Review

*Biomimicry in design-based learning*

Biomimicry is the application of biological structures and systems evolved by means of natural selection in the design process that could efficiently and effectively solve society's problems. A nature-inspired product is called a biomimetic [14-15]. One popular biomimetic is the cocklebur-inspired Velcro, created by George de Mestral. In nature, an excellent design has evolved for use when an organism encounters challenges in their environment that pressure them. As organisms go through this iteration process over generations, the best trait is selected, passed on, and gradually becomes dominant in such populations. These traits are a solution and a technology that helps organisms solve challenges easily to survive and thrive in demanding environments. Biomimicry, embodied in plants, animals, and other organisms, can inspire innovators to design sustainable technology.

This technology has been employed in product design and development for a long time. Innovators use a large number of biological models to reimagine and redesign human-built technologies. In search of a biological model, innovators must see organisms, such as plants, as an amazing technology themselves. Plants could store energy from the sun, move large amounts of water from the soil up without motorized pumps, and create materials out of the carbon dioxide in the air. To incorporate biomimicry into a design process, innovators identify and analyze a challenge imposed on humans from a biological perspective; then, they should seek and study biological models−a form, system, or process that has, at best, already solved a similar problem to help an organism survive and thrive in nature−to redesign solutions for the benefit of humans (6).

Biomimicry has been taught in higher-education architecture over many years [16] and has recently been introduced in K-12 STEM education. Incorporating biomimicry in design-based learning, a group of scholars proposed an instructional model called Biomimicry

Design Spiral (BDS) [17], in which teachers engage students in searching, analyzing, and utilizing biological strategies to inspire or redesign prototypes that could solve problems (Fig. 1). This process is nonlinear and iterative. BDS, which shares most of its procedure with the engineering design process [18-19] consists of six steps: define, biologize, discover, abstract, emulate, and evaluate. To define a challenge, students identify a problem and establish criteria and constraints that will determine success. To biologize, they think about essential functions and a context their design solution must address; they must then reframe these functions in biological terms. This would connect nature to the design. To discover, the students look for natural models, structures, or systems that address the same functions and explain how these could be applied to the context that their design solution must address. To abstract, they deeply study features or mechanisms that make biological strategies successful and examine the science behind them. To emulate, the students apply the patterns and relationships among such strategies to create a design concept or design a solution in action. To evaluate, they assess their process and prototype for how well they meet the criteria and constraints of the design challenge; then, they refine and revisit the previous steps as needed.

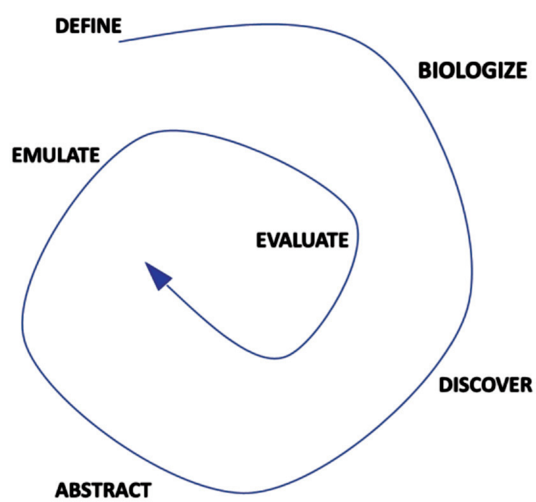



**Figure 1** The instructional model of Biomimicry Design Spiral (BDS)

## Materials and Methods

*Participants*

The participants (N=30) were recruited on a voluntary basis from 15 high schools in the central region of Thailand. Many of the schools were STEM regional centers (hereafter called STEM schools) that were established and funded by the IPST in 2013. These STEM schools provide training for teachers in their network. We recruited teachers from these STEM schools because they have participated in many integrated STEM education training sessions run by the IPST and have extensive experience in implementing STEM activities. That is, they are from schools that share the objective of our workshop, and these schools could support and facilitate the implementation of STEM activities. Many of these teachers were appointed by the IPST to be STEM ambassadors; they were trained to be trainers for integrated STEM education.

Two participants were recruited from each participating school. We also invited two IPST academic officials and two academic staffs from the National Science and Technology Development Agency in charge of STEM training to join the workshop as observers. We believed that each participant needed to have a partner from the same school so they could collaboratively push their learning experience from the workshop into practice in their contexts and become change agents in their schools [9, 20]. Of each teacher pair, one was a biology teacher, and the other was a teacher of other STEM areas. The literature suggests forming teams of teachers from different STEM disciplines to bring in different perspectives and expertise in implementing integrated STEM lessons. Furthermore, our intended pedagogy, biomimicry in design-based learning, requires knowledge on biological science. In the application process, we asked the teachers to fill out an online application form gathering details about their educational background, workload, previous STEM training, teaching experiences in integrated STEM and design-based learning, expectations from the professional development program to be held, and needs and challenges they had been facing in implementing integrated STEM education in their schools.

*Features of the workshop*

An intensive workshop was the professional development program used in this study. Although there is extensive literature identifying some disadvantages of this professional development activity, we believed it was the most feasible and appropriate option in our case considering multiple factors, such as time and financial constraints and the need of most of the participants. We encourage future studies to include a follow-up study involving on-site coaching and mentoring for the teachers after the workshop. We adopted many good practices in conducting an effective workshop from the literature [21-22]. In our workshop, the teachers were informed about the rationale for new teaching practices supported by research studies and why students were required to engage in purposeful collaborative design tasks. The workshop was rooted in adult learning, in which adult learners are self-directed, experienced, and intrinsically motivated. They were given instant and constructive feedback by the workshop instructors and other participants and informed about the conceptual and pedagogical understanding behind the activities and demonstrations. They were provided time and space to reflect upon their learning experience as well as concerns that may hinder the implementation of reform-based practices in their school contexts [22] such as students' individual differences, influences of high-stakes tests, and mandate of explicit and short-lived policies and procedures imposed on their schools. For these reasons, the implementation should be flexible and practical. Through a community of practitioners, they received possible solutions that supplement or align with their current practices, enabling them to develop a sense of ownership and aspiration.

*Workshop activities*

The workshop featured a special lecture on the application of biomimicry in innovation design and development. It was administered by an expert in bionic engineering known for his award-winning robotic fish and a fish tail-inspired power generator (Fig. 2A). In groups of three, the participants then engaged in a classic natural selection simulation activity, "the beak of the finch", in which each student selected a different tool that represented a different shape of a bird beak. Using this tool, they competed in picking up as much as possible of a given food, one unit at a time, in a 30-second period. In the subsequent rounds, the food was replaced by another type with a different shape and size. They repeated the whole process to find which beak shape was the most effective for a particular food. The instructor then introduced the theory of evolution by natural selection to help the participants explain their findings and showed them, through this natural process over time, the best trait that could help a living thing solve a challenge, performing a difficult function, effectively was selected. These traits could be used to inspire the design and development of an innovation. This was introduced as biomimicry. Subsequently, the participants were shown photos of living things that have interesting traits, one at a time, and then asked to think about biomimetic products inspired by such traits. They independently expressed their thoughts on a screen in real time (Fig. 2B) using CloudClassRoom (CCR), a web-based instant response system developed by Chien and Chang [23].

The engineering design process and the essential features of engineering tasks, synthesized from the literature review, were presented. We required the participants to read three scenarios about design tasks created by Capobianco, Nyquist, and Tyrie [24]. They were asked to identify problems and stakeholders in these situations, such as clients and end-users, conditions, and constraints. To implement the engineering design process in a biology classroom, we used an instructional model, Biomimicry Design Spiral (BDS) called BDS. We demonstrated a BDS-oriented lesson. In this demonstration, the participants were challenged to find the best way to dry small soda droplets in drinking straw eyeglasses using biomimicry. Following is the scenario of this design challenge.

In 2016-2017, a popular convenience store chain in Thailand sold a new product, a fancy eyeglasses straw that was so adored by kids across the nation. The straw, which came in different shapes, colors, and styles, could be worn by a child to drink carbonated drinks from a soda fountain. The kids collected, showed off, and traded these at schools. Although the convenience store no longer sells this product, children still ask their parents to buy them. Now, this kind of straw is sold online. The price can go from 50 baht (1.5 USD) for a plain one to 200 baht (6 USD) for a fancy one. Straws with many angles and curves are difficult to clean. Inappropriate cleaning of the straw leaves small water droplets trapped inside, which are a perfect living condition for disease-causing germs. Reusing unclean straws is unhygienic or even life-threatening. Help moms clean the fancy straw!!

So far, cleaning tools on the market cannot do the job well. Given the demand from moms and pub owners, designing and selling a tool that can effectively and efficiently clean this reusable fancy straw or those used for cocktails is a niche business opportunity. Suppose you and your team members are a team of product designers. You are required by your boss to design and develop an innovative cleaning tool that could earn the company a large profit with the below requirements and specifications.

Function: It must be effective in cleaning, leaving no water droplets or odor in the straw.

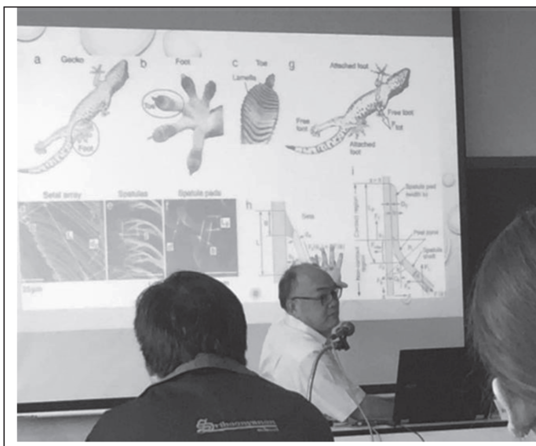
Conditions:

- It must not damage or wear out the straw during cleaning.
- It must be safe, easy, and quick to use (2 minutes maximum).
- It must outperform the available products on the market.

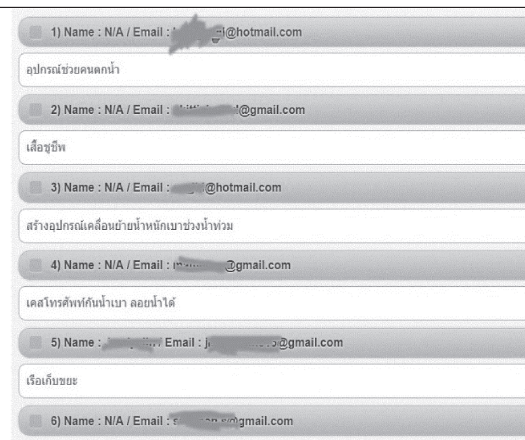
Constraints:

- The new product must be cheap, leaving a big margin (no less than 30 percent), but the price tag must be under 100 baht to ensure that moms can afford it.
- The materials must be locally sourced, environmentally friendly, and sustainable. This is the value added by the new product.
- The optimal design must be done in two hours. Remember, speed is a competitive advantage in business.

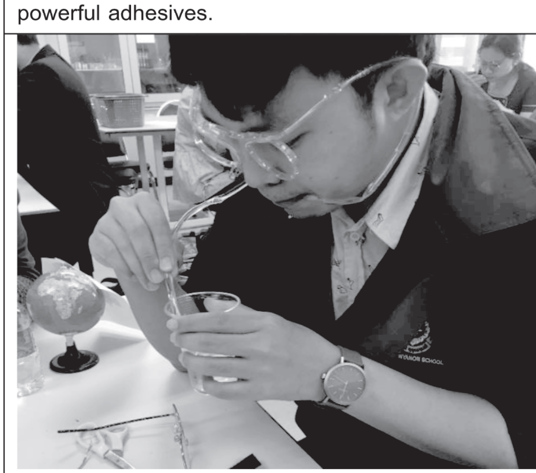
They worked in teams to analyze the situation and identify the problem, criteria of success, and limitations. They were given eyeglasses straws and soda to allow them to see, try, and test the real object (Fig. 2C). They generated solutions, selected the most promising options, designed prototypes, and tested and compared their results with those of the competing teams. They were asked to find any living thing with an interesting structure that might inspire them to solve the problem more effectively. They then redesigned and retested their prototypes. After the demonstrations, the participants reflected on the teaching approach and the instructional model underpinning the lesson. On the next day, the participants, in the same groups, designed their own BDS-oriented lessons (Fig. 2D). They created posters, presented these, and received comments and suggestions from the other teams in a gallery walk. The workshop ended with a discussion on the feasibility, challenges, and practicality of the implementation of biomimicry-incorporated STEM integration in biology in their schools.



(A) The invited speaker explains the science behinds geckos' sticky feet and the development of powerful adhesives.




(B) CCR is used throughout the workshop to assist the teacher in generating and sharing ideas in real time.



(C) A participant drinks soda with an eyeglasses straw and checks for leftover droplets.

(D) A team of teachers designs a BDS-oriented lesson.

**Figure 2** Photographs representing key activities in the workshop

*Data collection and analysis*

The instrument was an online survey called Teacher's Understanding of Engineering Design Process, which was administered pre- and post-workshop using the CCR platform. The survey was a Likert-type scale (3 = highly, 2 = somewhat, and 1 = not at all) with 17 statements intended to determine the degree to which the participants felt knowledgeable in each of the areas. The questions targeted common features of the engineering design process synthesized from the literature [25-28]. Their responses were analyzed by descriptive statistics.

## Results

The participants' responses to the statements about the features of the engineering design process in the online survey before and after the workshop are presented in Table 1. The results indicate that, in general, the participants already understood the engineering design process both the process and societal aspects before the workshop. More than 80 percent of them knew that designers need to research the challenges and existing solutions before determining solutions. They need to identify and consider the multiple perspectives from stakeholders. The teachers could distinguish between the criteria of success, constraints, and contexts and consider them during the design process. They knew what a prototype is and understood that the solution should be safe and beneficial for all stakeholders. The design process was a systematic inquiry, and their steps had no strict order. The participants understood the societal aspect of engineering design, including the need for a solution that would help innovators understand natural phenomena. This prior knowledge must have been developed from previous professional development opportunities provided constantly by the IPST. The high percentages of students holding these ideas were retained or slightly increased in the post-workshop response.

A positive change was found in some statements. The percentage of teachers who agreed on false statements decreased after the workshop. Those who believed that the engineering design process does not need to start with a question decreased from 43 to 14 percent. Those who previously thought that innovators create final products without making prototypes dropped from 29 to 7 percent. The teachers who believed that the process is iterative and sometimes messy increased from 29 to 43 percent. The participants who thought that, in solving a problem, innovators should overlook limitations to unleash creativity decreased from 52 to 11 percent, and those who believed that the product or procedure must have novelty increased from 10 to 39 percent. Notably, for the false statement "We must test all possible solutions", the percentage slightly decreased from 86 to 79 percent. The majority of the participants (79%) still held such misconception. In other words, the workshop was unlikely to have impacted their view on this issue.

**Table 1** Percentage of the participants who agreed with the statements about the engineering design process before and after the workshop

| What is true about the engineering design process? | % Pre | % Post |
|---|---|---|
| 1. We do not need to have a question.* | 43 | 14 |
| 2. We must research the problem. | 86 | 96 |
| 3. We must identify as many solutions as possible or at least several options. | 95 | 96 |
| 4. We must consider the views of stakeholders in solving a problem. | 90 | 93 |
| 5. We must test all possible solutions.* | 86 | 79 |
| 6. We must design a model/prototype. | 90 | 93 |
| 7. We do not need to have a model/prototype; just make a product right away.* | 29 | 7 |
| 8. There is no strict order or steps in solving a problem.* | 10 | 0 |
| 9. The process is iterative and sometimes messy. | 29 | 43 |
| 10. Solving a problem would help us understand natural phenomena. | 90 | 96 |
| 11. The solution must be safe. | 86 | 96 |
| 12. The solution must be helpful for affected/related stakeholders. | 100 | 100 |
| 13. The prototype comprises many parts with different functions working together. | 100 | 100 |
| 14. We should not consider limitations because doing so would narrow our thoughts.* | 52 | 11 |
| 15. Constraints and conditions are different. | 81 | 96 |
| 16. The solution must always be a new product or procedure. | 10 | 39 |
| 17. Inquiry is a part of the engineering design process. | 90 | 93 |

* indicates a reverse statement.

## Conclusion and Discussion

Overall, prior to the workshop, the teachers had a strong background on the engineering design process since they were working in STEM schools. They had attended many professional development programs provided by the IPST about integrated STEM education and had plenty of experience implementing STEM lessons themselves. They must have engaged in STEM lessons as students and teachers to have learned many essential characteristics of integrated STEM and the engineering design process, as evidenced by the large percentage of them having a sound understanding of STEM characteristics in the pre-workshop survey. These teachers must have had a framework that helped them make sense of the training experience in the workshop. It could have been structured by their existing knowledge. Their knowledge was reinforced by engaging in a new design challenge. As for the ideas that were developed in the workshop, such as the need of the design task for a problem and the reality that the problem always comes with limitations (including conditions and constraints), there was an increase in the number of teachers holding these ideas after the workshop. In the workshop, the teachers read three scenarios as practice design tasks and the fancy straw cleaning task, the main design challenge. They were asked to identify a problem and analyze the situation to identify the required product functions and the conditions and constraints for consideration. They spent a lot of time on this task analysis, and the workshop instructor asked them to ensure that they were clear about the task before proceeding to the next step. For an explicit task analysis, the instructor used a function, conditions, and constraints (FCC) table. This technique helped the students distinguish between these components, which are often confusing for learners. The FCC was consulted and taken into account throughout the project. There are more teachers by the end of the workshop paying attention to the novelty of a product. In light of this, the teachers were asked to research available solutions. In one of the given conditions, the solution needed to outperform existing products on the market. This may have urged them to be more creative in their designs. The teachers were then asked to generate and test ideas with prototypes. They started by drafting their ideas on paper, elaborating them, and creating prototypes. They used these prototypes to communicate their ideas to the other teams. This may have changed some teachers' belief regarding prototypes; initially believing that a prototype is unnecessary, they eventually expressed that a prototype has to be made and tested before producing a real product. They improved their prototypes many times to obtain the optimal design. Some groups had to step back to check with the literature and change directions unexpectedly. This may have made them realize that the design process is iterative, nonlinear, and more sophisticated than they had imagined. These new learning experiences can be structured by corresponding features of the engineering design process put forth before engaging in the design challenge and during the reflection session. According to the framework of the conceptual change model, experience was intelligible and fruitful for the participants; thus, they changed their views on their prior misconceptions [29].

A feature of the engineering design process that is hard to change is that all possible solutions must be tested; most of the teachers held this misconception before and after the workshop. They may have thought that, if the first solution does not work, they should opt for the next promising option until they obtain the best solution. This idea is partially true but does not work in reality because there could be many options but they had limited time. Therefore, they need to prioritize all options and select the most promising one to design and test it. This point was discussed during the reflection session, but they still held their existing knowledge. Their idea was resistant to change. This can be explained by Chin and Brewer's notion [30] that people are more likely to discount new experiences in various ways to protect their pre-instructional view, such as by ignoring, rejecting, excluding, and suspending the new information.

Another feature of engineering design process that the majority of the participants still holding misconception after the BDS workshop is that the engineering design process is iterative and sometimes messy, even though there is an increase in the percentage of participants holding sound understanding from 29 to 43 percent. This might have caused by time constraint of the workshop. They actively and fully engaged as students in only one design challenge, the fancy straw challenge. As such, they might have not experienced that the design process was iterative. They had only one or two rounds to redesign and retest to improve their prototype and retest it. In addition, they did not see and experience that engineering design process was often messy but mistakenly, being a linear, stepwise process. The authors thought that if workshop instructors had introduced several other case studies of the design process of great biomimetic designs such as Kingfisher and the Shinkansen, Birds and flight, Lotus-inspired hydrophobia during the reflection session, the teachers would have understood this feature better.

## Implication

Design-based learning-integrated biomimicry is an approach to fostering $21^{st}$ century skills and sustainability. It helps bring together two disciplines that seem hard to integrate biology and engineering to create innovative designs and products. Biomimicry could be integrated in the engineering design process to further improve a prototype and usually make the final product more environmentally friendly and in harmony with nature. Biomimicry could address biology teachers' fear and concern and encourage them to attempt something challenging but beneficial for their students. To implement design-based learning with biomimicry effectively, biology teachers need to have a deeper and more connected level of content knowledge in their own disciplines and a deeper understanding of science and engineering practices, including the engineering design process. Biology teachers should train and urge students to use analogical, creative thinking and critical thinking in biomimicry methodology. In this manner, their students could discover and integrate biological forms, processes, or systems directing preferred functions when attempting to solve a design need. These higher-order thinking will enable them to confirm and evaluate the sustainability of their designs. Teachers will feel supported to enact this reformed practice through collaboration with peers, quality-integrated curricula, administrative and technical support, and effective professional development.

Based on the findings of the present study, the authors would like to propose a model for an effective professional development program (PD) that would sustain their understanding and help teachers enact what they learned from the professional development program in their classroom more fruitfully. The PD should prolong, be collaborative, reflective, and conducted in job-embedded context. The workshop like the one in this study was a single and intensive shot but did not provide further support once the participants came back to their classroom. A professional developer should provide coaching and mentoring on site, so the teachers would be offered constructive feedback on their practice constantly and instantly, be facilitated reflection on a new teaching strategy and get mental support. The professional developer should also establish professional learning community (PLC) in their school. It could empower peer collaboration in their job. PLC is an ongoing process in which teachers work collaboratively in a safe and healthy environment using collective inquiry to reflect on their issues in their teaching to improve their practice and student learning. This collaborative PD is a source of efficacy and confidence for teachers and can result in widespread improvement within and beyond their classroom.

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