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Teacher Training Guidelines on Green Chemistry Based on the Technological Pedagogical Content Knowledge (TPACK)

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This study developed an expert-consensus-based guideline to address teacher preparedness in implementing green chemistry and sustainability goals in Malaysian education. It is structured around the three Technological Pedagogical Content Knowledge (TPACK) basic domains: Content Knowledge (CK), Pedagogical Knowledge (PK), and Technological Knowledge (TK). To ensure equal participation and build a structured consensus via online from a multidisciplinary expert panel, a descriptive research design was implemented using the modified Nominal Group Technique (mNGT). There are seven experts across Green Chemistry, pedagogy, educational technology, and curriculum who participated in this study. The research undergoes five steps, including an introductory session, idea generation, online group discussion, voting, and findings presentation to collect data. The data were analyzed using descriptive statistics (scores, percentages). Key findings regarding TPACK identified the following priorities: for CK, four Kurikulum Standard Sekolah Menengah (KSSM) chemistry topics, two GC principles, and four training supports; for PK, four teaching approaches and eight PK training supports; and for TK, two immersive technologies, three digital tools, and four training supports. The proposed green chemistry training guideline, as a roadmap for the Ministry of Higher Education, prepares teachers to integrate green chemistry concepts into chemistry classroom instruction.

Keywords: green chemistry, teacher training guideline, TPACK, modified nominal group technique, content knowledge, pedagogical knowledge, technological knowledge

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INTRODUCTION

Green chemistry promotes sustainability and aligns with the Sustainable Development Goals. Therefore, education plays a crucial role in raising awareness and advancing green chemistry principles. Integrating green chemistry and sustainability into primary, secondary, and higher education is an urgent step to support these efforts (Gomes & Zeidler, 2023; Li & Eilks, 2021). Many countries have added green chemistry to curricula through hands-on activities, teacher training, and informal education programs. In Malaysia, green chemistry concepts are included in the KSSM syllabus (KPM, 2018). However, their implementation remains superficial (Taha et al., 2021). It still mainly focuses on traditional experiments, with little emphasis on the 12 principles of green chemistry (Patah et al., 2023).

Teachers' competence is the key to making education more meaningful (Latip et al., 2023). However, teachers often face challenges such as insufficient content mastery, a lack of pedagogical strategies, heavy workloads (Saraih et al., 2024), and limited training resources (Carangue et al., 2021; Ibrahim et al., 2025). Existing teacher training programs in Malaysia tend to be theoretical (Armstrong et al., 2024), brief, and lacking follow-up, practical application, and technological skill sharpening (Shurygin et al., 2022). As a result, many teachers feel unprepared to teach green chemistry effectively.

Therefore, this study aims to fill the gap in Malaysia's green chemistry education by identifying key elements and proposing a TPACK-based teacher training guideline. Focusing on three main domains which are Content Knowledge (CK), Pedagogical Knowledge (PK) and Technological Knowledge (TK), the framework equips chemistry educators with 21st-century teaching skills, preparing students to face modern scientific challenges. By accommodating teachers' varying strengths and weaknesses, the guideline supports curriculum reforms, advances SDG 4 on quality education, and contributes to sustainability goals. As there is a need for a step-by-step teacher training guideline, focusing on the three main domains is more suitable to be used in this study.

LITERATURE REVIEW

Green Chemistry Education

Green chemistry was introduced in the early 1990s (Laurensia, 2024). It has gained global acceptance and was included in global educational programs to promote sustainable chemical practices that reduce hazardous substances and environmental impacts (Ibrahim et al., 2025; Koulougliotis et al., 2024; Taha et al., 2021). Guided by Anastas and Warner's 12 principles (Patah et al., 2023), its implementation improves students' environmental attitudes, beliefs, and behavior (Karpudewan, 2020) while enhancing their understanding of chemistry and argumentation skills (Koulougliotis et al., 2024).

In Malaysia, green chemistry education started with Environmental Education in primary schools in 1982 and later expanded across school levels to foster sustainability awareness (Taha et al., 2021). Despite these efforts, curriculum integration remains limited (Taha et al., 2021). Burmeister et al. (2012) proposed four models for integrating green chemistry into education: (I) adopting green chemistry principles in laboratory practices, (II) contextualizing chemistry content through a green chemistry theme, (III) using socio-scientific issues-based projects that incorporate green chemistry practices, and (IV) taking a holistic approach to sustainability in education. Among these, Model II is especially relevant because it connects chemistry concepts with real-world environmental issues like biodegradable plastics and biofuels. This approach motivates students to learn chemistry and sustainability through innovative teaching. and context-based.

As the "central science", chemistry provides an ideal platform to integrate sustainability and develop students' scientific problem-solving and higher-order thinking skills to address environmental challenges (Karpudewan, 2020). However, many studies highlight a lack of clear strategies and teacher guidelines for effectively implementing green chemistry education in the classroom (Ibrahim et al., 2025). To address this gap, the present study uses the TPACK model to develop a training framework that enhances teachers' technological, pedagogical, and content knowledge to advance green chemistry education.

Teacher Preparedness in Teaching Green Chemistry

Teacher preparedness is crucial for implementing green chemistry education (Taha et al., 2021). It reflects teachers' ability to incorporate sustainability concepts into their teaching through theoretical knowledge, pedagogical skills, and practical laboratory experience (Ibrahim et al., 2025). However, research shows that teachers often have only superficial knowledge of green chemistry and are unfamiliar with the 12 principles (Carangue et al., 2021; Ibrahim et al., 2025). For example, Carangue et al. (2021) found that while over 60% of participants correctly answered items on the purpose (75.83%), applications (74.67%), and environmental issues (65.33%) of green chemistry, they struggled with its principles, tools, and concepts. This hinders practical application and the achievement of the sustainability goal.

Additionally, many teachers encounter green chemistry only after they graduate (Ibrahim et al., 2025). It is often regarded as an elective rather than a core subject (Marques et al., 2020). Although most teachers agree on its importance for fostering students' environmental awareness, limited pedagogical skills and uncertainty constrain classroom implementation (Ibrahim et al., 2025; Taha et al., 2021). These issues underscore the need for comprehensive teacher training to bridge the gaps and promote the adoption of green chemistry education. Therefore, this study examines the specific components of TPACK that are required for teacher training to enhance teachers' readiness and confidence.

TPACK Framework In Teacher Training

The continuous advancement of technology and its integration into daily life highlight its growing importance in the educational field (Timotheou et al., 2022). Accordingly, the Technological Pedagogical Content Knowledge (TPACK) framework addresses a critical 21st-century need by providing a validated structure for integrating technology into teaching (Latip et al., 2023), especially in primary and secondary education (Fahadi & Khan, 2022). This is particularly emphasized in contemporary Malaysian education

(Ahmad & Rathakrishnan, 2025) as TPACK is an essential competency for teachers (Kumala et al., 2022). The TPACK is particularly relevant for chemistry education as it enables teachers to enhance students' scientific reasoning and problem-solving skills systematically through technology (Meletiou-Mavrotheris & Paparistodemou, 2024). For instance, Purba et al. (2023) found that TPACK guides teachers in employing animations, videos, and simulations to clarify the multiple levels of representation in chemistry (macroscopic, submicroscopic, and symbolic), thereby enhancing student motivation and conceptual understanding (Meletiou-Mavrotheris & Paparistodemou, 2024).

The TPACK framework elaborates on Shulman's (1987) Pedagogical Content Knowledge (PCK) model by integrating a technology component into teaching and learning (Bernardes & De Andrade Neto, 2021). The TPACK framework can be represented as in Figure 1.

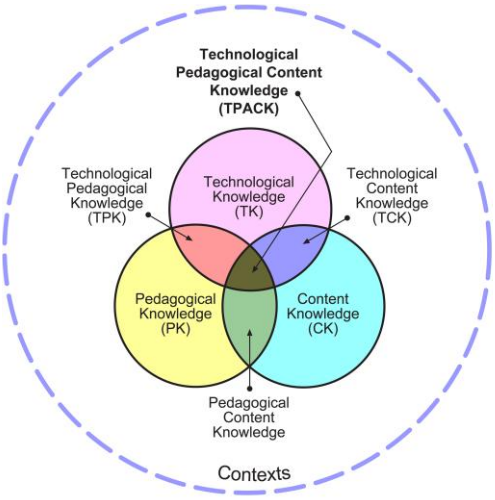

Figure 1
TPACK framework by Mishra and Koehler (2006)

The TPACK framework consists of seven domains. These include:

a. Content Knowledge (CK), which outlines the topic to be taught or learned;

b. Pedagogical Knowledge (PK), which relates to the teaching approach;

c. Technological Knowledge (TK), which shows the skills in handling the technology;

d. Pedagogical Content Knowledge (PCK), which refers to teaching strategies for presenting various subject matter;

e. Technological Content Knowledge (TCK), which shows how technology enhances or limits content delivery;

f. Technological Pedagogical Knowledge (TPK), which corresponds to strategies for pedagogical action with technology;

g. Technological Pedagogical Knowledge Content (TPACK), which shows good teaching content with the use of technology (Koehler & Mishra, 2006; Latip et al., 2023).

For constructing a training guideline, the framework's base knowledge domains (CK, PK, and TK) serve as the essential and actionable pillars in this study. By structuring training around these domains, it allows for building up teachers' existing knowledge gradually, scaffolding their training from basic pedagogy and content knowledge to advanced technological integration. This sequenced approach directly supports the development of a coherent training program that effectively incorporates green chemistry into instruction. Therefore, this study aims to investigate the elements needed in the basic domains that can be integrated into green chemistry education.

METHOD

Research Design

This study employed a descriptive research design using Modified Nominal Group Technique (mNGT) to identify suitable elements for teacher training programs based on TPACK, focusing on Technological Knowledge (TK), Pedagogical Knowledge (PK), and Content Knowledge (CK). This approach allows the collection of experts' opinions from diverse perspectives to pinpoint key elements or solutions for the research topic and plan for their implementation (Ridzuan et al., 2023; Yahaya et al., 2020).

Research Experts

The study employed purposive sampling to select participants from Johor, Malaysia, based on two criteria: (a) at least five years of professional experience in the relevant field (green chemistry, educational technology, pedagogical knowledge), (b) direct lived experience in the respective field. The study integrates input from three expert roles: (a) Green Chemistry Expert (CK) provides the necessary content knowledge; (b) Educational Technology Expert (TK) identifies applicable teaching tools; and Teaching Expert (PK), as chemistry teachers will be trained via the proposed guideline, delivering the final instruction to students to ensure effective skill acquisition. Initial invitations were extended to 2-3 pre-identified experts from each target field. Following non-responses, a second round of invitations was issued to ensure adequate representation. The final panel consists of seven experts, aligning with mNGT principles and Vahedian et al.'s (2023) recommendation of four to seven participants for effective discussion. They represent diverse specializations in green chemistry, educational technologies, KSSM chemistry content, pedagogy, and direct involvement in teacher training. Table 1 shows the list of experts involved in mNGT.

Table 1
List of experts involved in mNGT

Expert	Position	Field of Expertise
E1	Lecturer	Green Chemistry content
E2	Lecturer	Educational technology Direct involvement in training teachers
E3	Lecturer	Educational technology Direct involvement in training teachers
E4	Form 4-5 Chemistry teacher	KSSM Chemistry content expert KSSM Chemistry content implementor Pedagogical knowledge
E5	Form 4-5 Chemistry teacher	KSSM Chemistry content expert KSSM Chemistry content implementor Pedagogical knowledge
E6	Secondary school teacher	Educational technology Pedagogical knowledge
E7	Secondary school teacher	Educational technology Pedagogical knowledge

From Table 1, each expert's expertise field is tabulated. The criteria of the expert in this study contained: (1) two educational technology experts, (2) two teaching strategies experts, (3) a green chemistry content expert, and (4) two KSSM content experts and implementors. This cross-disciplinary panel was engaged to validate and cross-check insights, thereby strengthening the reliability and validity of the findings. The professionals' involvement provides valuable insight to bridge the gap between theory and classroom practice and suggests practical recommendations for green chemistry teacher training. While the Johor-based panel ensured contextual depth, its localized composition may limit the applicability of findings to other regions or national contexts

Research Procedure

This study used a descriptive research design through Modified Nominal Group Technique (mNGT) as outlined by Ridzuan et al. (2023). The research procedure is shown in Figure 2.

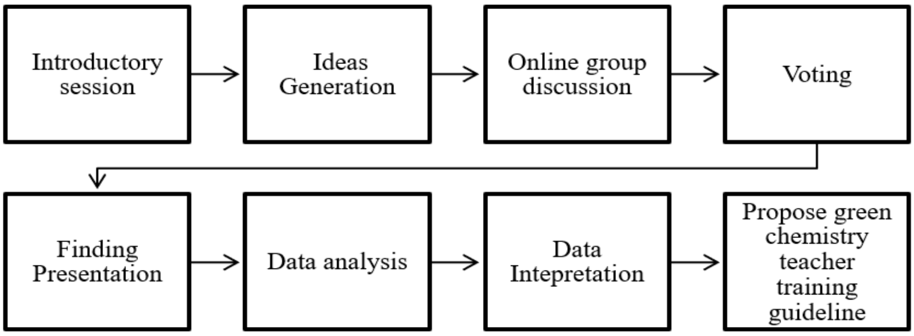

Figure 2
Research Procedure

As shown in Figure 2, the research began with an introductory session where experts were briefed via a WhatsApp group using a documentary that explained the research goals, background, problem statements, and gaps. Next, during the silent idea generation phase, experts answered an open-ended mNGT questionnaire within two weeks using Microsoft Word, focusing on sub-elements to improve teachers' CK, PK, and TK. To guide their responses and avoid delays, appendices listing current technological, pedagogical, and content knowledge in green chemistry were provided (Zakaria et al., 2025). The third step was an online group discussion via Google Meet to refine the proposed sub-elements by revising, adding, or removing items. A pre-shared draft helped shorten the discussion time from the usual 240 minutes in traditional NGT to 90 minutes (Mousa et al., 2022; Zakaria et al., 2025). The discussion was moderated by researchers, while an assistant recorded the revisions. Experts reviewed ideas through agreement, disagreement, or suggestions until reaching a consensus. Afterward, a voting session was conducted using a 7-point Likert scale in Google Sheets, which automatically calculated scores and percentages. Items with ≥70% agreement were accepted (Deslandes et al., 2010; Yahaya et al., 2020), showing stronger consensus and prioritization. Results were presented immediately for expert review to ensure accuracy and explore reasons for prioritization. Finally, the data was analyzed to confirm acceptance or rejection of each sub-element, and the research concluded with a guideline proposing the key elements and sub-elements for green chemistry teacher training.

Research Instrument

As mNGT involves the idea generation and voting phases, two instruments are needed for data collection. An open-ended questionnaire to produce effective brainstorming (Winggins et al., 2020), followed by a voting form for arranging them in quantitative priority order. These instruments identified the knowledge required to enhance green chemistry teacher training in the technology, pedagogy, and content aspects. Both were validated by two experts in modified Nominal Group Technique (mNGT) and green chemistry to ensure relevance, coherence, and alignment with research objectives, thereby making the collected data accurate and reliable (Pino et al., 2023).

Idea Generation Form

The open-ended questionnaire consists of 3 sections. All the questions were adapted from the TPACK semi-structured interview schedule of Bwalya et al. (2023). There are three types of knowledge: Content Knowledge (CK), Pedagogical Knowledge (PK), and Technological Knowledge (TK), which align with the study's research questions. Section 1 explored the CK needed for green chemistry teacher training through 2 items: relevant KSSM Chemistry topics and green chemistry principles. Section 2 assessed PK in terms of teaching approaches. Section 3 determined the TK across 2 aspects. There are immersive technologies and digital tools.

Voting Form

The results were then ranked using a 7-point Likert scale (1 = least favorable, 7 = most favorable) to reflect experts' preferred choice, lessen overlap, and give the experts a greater chance to decide on the priority (Yahaya, 2020). The voting form was created in

Google Sheets, with eight labeled sheets, each representing one subconstruct, to ease the voting process.

Data Analysis

Idea Generation

Qualitative data in Idea Generation were thematically analyzed to identify, organise and interpret the themes. Keywords in each raw data were identified to generate a theme. Figure 3 shows an example of thematic analysis that was carried out.

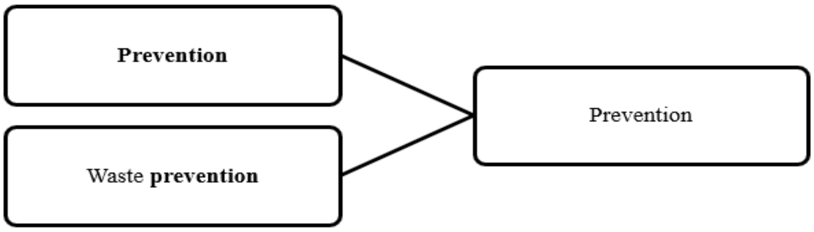

Figure 3
An example of thematic analysis in the idea generation phase

The themes for each element were validated and refined through expert group discussions to ensure they accurately reflected the experts' intended meaning.

Online Group Discussion

The responses for online group discussion will be extracted and coded in the form of a transcript as a prove of relevant content. The coding notified the element discussed (in front of the semicolon) and the expert response to (after the semicolon). For example, the coding of C1; E1, C1 refers to the first CK element, while E1 refers to expert 1. It shows the answer from expert 1, who is a green chemistry expert, for the first CK element, which is the KSSM chemistry topics for green chemistry integration. The respondent can refer to a list of experts in Table 1 above. The code meaning of the aspects is shown in Table 2.

Table 2
Coding the meaning for elements

Code	Elements
C1	KSSM chemistry topics for green chemistry integration
C2	Green chemistry principles for KSSM syllabus alignment
C3	CK training support
P1	Effective teaching approach
P2	PK training support
T1	Types of effective immersive technologies
T2	Types of effective digital tools
T3	TK training support

Table 2 outlines coding for all three themes. Transcript coding is important to ensure that the correct sources are cited and to facilitate clear reading.

Voting

At this stage, quantitative data were analyzed descriptively by ranking the items based on total scores and percentages. The percentages were calculated using Google Sheets (see Formula 1 in Appendix A). To auto-generate the ranking (priority) using Google Sheets based on the percentage of each element, a priority formula was used (see Formula 2 in Appendix A). This equation operates on two things: (1) checks the condition of the percentage and (2) ranks the value if the condition is ≥ 70%. The higher the percentage is, the more in front the ranking, and the element is more prioritized.

FINDINGS AND DISCUSSION

The following results were collected through mNGT. After the idea revisions in online group discussions, the revised elements underwent voting and the results will be discussed based on construct Content Knowledge (CK), Pedagogical Knowledge (PK) and Technological Knowledge (TK).

Content Knowledge

Table 3 shows the voting result for CK elements.

Table 3
Voting result on the revised elements of CK after group discussion

Elements	Items	Total score	Percentage (%)	Acceptance status	Ranking
KSSM Chemistry Topics for Green Chemistry Integration	1. Organic Chemistry	45	92	Accepted	2
	2. Acids, Bases and Salts	41	84	Accepted	4
	3. Polymer	42	86	Accepted	3
	4. Consumers and Industrial Chemistry	49	100	Accepted	1
Green Chemistry Principles for KSSM Syllabus Alignment	1. Prevention	49	100	Accepted	1
	2. Safer solvents and auxiliaries	44	90	Accepted	2
	3. Designing safer chemicals	23	47*	Rejected	-
	4. Design for degradation	34	69*	Rejected	-
	5. Real-time pollution prevention	31	63*	Rejected	-
CK Training Support	1. Prevention	49	100	Accepted	1
	2. Designing safer chemicals	24	49*	Rejected	-
	3. Design for degradation	28	57*	Rejected	-
	4. Real-time pollution prevention	30	61*	Rejected	-
	5. Workshops	42	86	Accepted	3
	6. Teaching resources and a laboratory manual	45	92	Accepted	2
	7. Funding of the green chemistry experiment	34	69*	Rejected	-
	8. Collaborative training with an experienced educator	42	86	Accepted	3

In Table 3, experts emphasized topics that connect directly to daily life and raise students' environmental awareness. One key topic was *Consumers and Industrial Chemistry* (100%), which links consumer behavior with industrial production and sustainability was strongly recommended. It involves industries such as food, cleaning agents, cosmetics, nanotechnology, and green technology, encouraging greener processes and waste reduction (KPM, 2018). Other topics, such as *Organic Chemistry* (92%), *Polymers* (86%), and *Acids, Bases, and Salts* (84%), were also identified as suitable for integrating green chemistry principles. Based on previous research by Etzkorn & Ferguson (2022), Beker (2023) and Olanrewaju & Adeosun (2023), all researches agree that these topics are aligned with green chemistry principles to promote a safe and sustainable environment. From the 12 principles, only *Prevention* (100%) and *Safer Solvents and Auxiliaries* (90%) were unanimously recommended because they are easier to apply, given limited expertise and resources. Training in CK should therefore focus on these principles, provide resources for safe chemical handling, and build teacher confidence and subject knowledge through hands-on and collaborative learning (Cannon et al., 2021). Mitarlis et al. (2023) demonstrated that both principles can be seamlessly embedded in secondary chemistry, particularly Form 4 Chapter 1 (Introduction to Chemistry), which spans chemical and physical properties of elements, compounds, mixtures, stoichiometry, titration, indicators, and electrolytes. For acid–base titration, the "prevention" principle is implemented by using small-scale reagents to minimize waste, while "safer solvents and auxiliaries" can be practiced by preparing natural indicators. Similarly, when teaching elements, compounds, and mixtures, chemical quantities can be reduced to prevent waste, and iodine in sublimation may be replaced with naphthalene as a safer auxiliary. These strategies are transferable across other chemistry topics.

Pedagogical Knowledge

Table 4 shows the voting result for PK elements.

Table 4
Voting result on the revised elements of PK after group discussion

Elements	Items	Total Score	Percentage (%)	Acceptance status	Ranking
Effective Teaching Approach	1. Project-based Learning (PJBL)	43	88	Accepted	2
	2. Experiential Learning	38	78	Accepted	4
	3. Inquiry-based learning (IBL)	29	59*	Rejected	-
	4. Problem-based learning (PBL)	34	69*	Rejected	-
	5. Case-based learning (CBL)	44	90	Accepted	1
	6. Socio-Scientific Issues-Based Learning (SSI)	42	86	Accepted	3
PK Training and Support	1. Workshop	44	90	Accepted	2
	2. Training in designing an appropriate assessment for the students	24	49*	Rejected	-
	3. Institutional support to include green chemistry in the syllabus	25	51*	Rejected	-
	4. CBL-Focused Training	39	80	Accepted	4
	5. PJBL-Focused Training	41	84	Accepted	3
	6. Mentorship	41	84	Accepted	3
	7. Peer collaboration network	41	84	Accepted	3
	8. Support from school and peers	38	78	Accepted	5
	9. Curriculum-aligned lesson plans	47	96	Accepted	1
	10. Provision of green chemistry resources	31	63*	Rejected	-
	11. Professional development session	38	78	Accepted	5

Based on Table 4, experts agreed that student-centered approaches are more effective in green chemistry education. Recommended strategies include Case-Based Learning

(CBL) (90%), Project-Based Learning (PJBL) (88%), Socio-Scientific Issue-Based Learning (SSI) (86%), and Experiential Learning (78%). Among these, CBL was prioritized because it uses real-world cases with clear problems and solutions, making lessons relatable and structured. Training should also emphasize curriculum-aligned lesson plans (96%), which help teachers connect theory with practice while maintaining alignment with national standards (Lazarous et al., 2025). Mitarlis et al. (2023) further highlight that the lesson plans offer valuable practical guidance for designing and implementing effective green chemistry instruction.

Technological Knowledge

Table 5 shows the voting result for TK elements

Table 5
Voting result on the revised elements of TK after group discussion

Elements	Items	Total score	Percentage (%)	Acceptance status	Ranking
Types of Effective Immersive Technologies	1. 3D interactive model	33	67*	Rejected	-
	2. Gamified learning platform	38	78	Accepted	1
	3. Virtual field trip	37	76	Accepted	2
	4. Virtual reality simulation	30	61*	Rejected	-
Types of Effective Digital Tools	1. Multimedia resources	49	100	Accepted	1
	2. Website and online platforms	49	100	Accepted	1
	3. Software	34	69*	Rejected	-
	4. Online assessment tool	33	67*	Rejected	-
TK Training and Support	1. Training in using software/digital tools	30	61*	Rejected	-
	2. Pedagogical support/guidance to improve student engagement	31	63*	Rejected	-
	3. Software	24	49*	Rejected	-
	4. Virtual chemistry laboratory	26	53*	Rejected	-
	5. Peer collaboration network	40	82	Accepted	2
	6. Peer Learning Coaching (PLC)	43	88	Accepted	1
	7. Regularly conducted online courses or workshops	38	78	Accepted	3
	8. Assessment tool for laboratory use	37	76	Accepted	4

Based on Table 5, experts highlighted practicality, usability, and access to equipment. The most recommended digital tools were *multimedia resources* (100%) and *website and online platforms* (100%), while immersive technologies such as *gamified learning platforms* (78%) and *virtual field trips* (76%) while also recommended. These recommended tools are valued for being free and accessible. Multimedia specifically shown to enhance cognitive outcomes, as students perform better in topics like "Acids and Bases" when teachers use such resources (Menno & Prodjosantoso, 2025). Gamified platforms motivate students and teach safer chemical design through experiential learning (Chantal & Kiu, 2024), while virtual trips allow building students' awareness of green chemistry through safe exploration of remote industrial sites (Chiu, 2021). For example, the DSKP Chemistry (KPM, 2018) proposes field trips to rubber-based industries to teach the applications of natural and synthetic rubber, as it is safe to connect theory to practice. Although VR can enhance learning (61%), it is often impractical in schools due to high costs and technical barriers. This results aligned with

Aziz et al. (2024), who claimed similar challenges for virtual labs. Instead, Peer Learning Coaching (PLC) received the strongest support (88%) as an effective and sustainable approach. PLC encourages peer-to-peer sharing, feedback, and reflection, which collectively improve both TK and PK (Elizov & Jarvis, 2025).

Overall, the findings indicate that experts prefer structured, collaborative, and practical training approaches. Elements that were rejected were generally those lacking relevance, feasibility, or clear contribution to skill development.

Proposed Teacher Training Guideline

The guideline shown in Figure 4 is the final result of voting based on expert-accepted elements and sub-elements essential for integrating green chemistry into chemistry education.

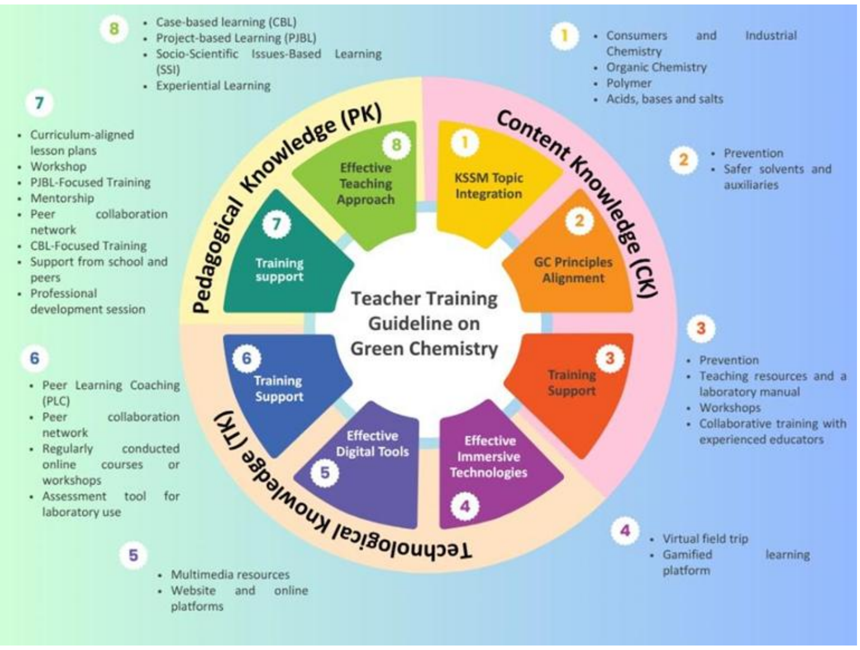

Figure 4
Proposed teacher training guideline

Based on Figure 4, the framework is organized into three main domains of the TPACK framework. Items inside the circle represent each element for CK, TK, and PK. In contrast, items outside the circle refer to sub-elements that strengthen each corresponding element, labeled with the same number.

For CK, three key elements are identified: Element 1 (KSSM Topic Integration) focuses on embedding green chemistry concepts into core topics such as *Consumers and Industrial Chemistry, Organic Chemistry, Polymers*, and *Acids, bases, and salts*. Element 2 (GC Principles Alignment) highlights the green chemistry principles suitable for integration into the selected topics, specifically *Prevention* and *Safer solvents and auxiliaries*. Element 3 (Training Support for CK) enhances teachers' knowledge of green chemistry by utilizing prevention strategies, teaching resources, laboratory manuals, workshops, and collaborative training with experienced educators.

TK includes Element 4 (Effective Immersive Technologies), which involves virtual field trips and gamified learning platforms; Element 5 (Effective Digital Tools), such as multimedia resources, websites, and online platforms; and Element 6 (TK Training Support), which covers sub-elements like Peer Coaching Learning (PLC), peer collaboration networks, regularly conducted online courses and workshops, and assessment tools for laboratory use.

The last two are part of PK, with Element 8 (Effective Teaching Approaches) outlining methods such as Case-Based Learning (CBL), Project-Based Learning (PBL), Socio-Scientific Issues-Based Learning (SSI), and Experiential Learning. Element 7 (PK Training Support) aims to improve teachers' PK through curriculum-aligned lesson plans, workshops, PJBL-focused training, mentorship, peer collaboration networks, CBL-focused training, support from schools and colleagues, and professional development sessions.

The proposed teacher training guideline, grounded in an integrated Technological Pedagogical Content Knowledge (TPACK) framework, has significant research implications for professional development in chemistry education. Specifically, it underscores that comprehensive, sustained teacher education interventions designed to concurrently develop content, pedagogical, and technological knowledge are empirically associated with meaningful improvements in teachers' integrated professional knowledge, which is critical for effective curriculum implementation and instructional innovation. This is similar to the findings of Ning et al. (2022) showed a strong positive effect of such interventions on TPACK development when teachers are provided sustained and targeted professional learning opportunities combining content, pedagogical strategies, and technology use.

CONCLUSIONS AND FUTURE WORK

This study employed a descriptive research design using the Modified Nominal Group Technique (mNGT) to propose a structured guideline for green chemistry teacher training based on three basic domains of the TPACK model: Content Knowledge (CK), Pedagogical Knowledge (PK), and Technological Knowledge (TK). For CK, the guideline illustrates four KSSM topic integrations, two green chemistry principles, and four CK training supports. In PK, it emphasizes four effective pedagogical approaches, along with eight training supports, while TK focuses on two effective immersive technologies, two effective digital tools, and four TK training supports. It serves as a valuable roadmap and practical reference for teachers and the Ministry of Higher Education in teacher training, to instill green chemistry concepts into the current chemistry curriculum. It is believed that, with continued training, students, the general public, and the country will be educated by teachers to gradually develop a deeper understanding and commitment to green chemistry practices. Despite its contributions, the study is limited by its focus on individual basic core domains without addressing their interactional domains (TPK, TCK, PCK). Additionally, the purposive sample of this study consisted of only seven experts, limiting the generalizability of the findings. Therefore, the results may not be suitable to be applied to every teacher or training program. To address this, the group of expert respondents can be expanded to at least two in the future to cross-check the results, thereby ensuring reliability and practicality. Moreover, it lacks empirical validation in classroom settings. Future research should therefore explore the intersections of the core TPACK domains (TCK, TPK, PCK, and TPACK) to develop a more comprehensive. The proposed guideline should be tested through staged classroom trials to ensure its empirical validation for instruction.

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APPENDIX A

Formulas for Voting Results

To get the voting result, two formulas were used, which are the percentage formula (see Formula 1) and the priority formula (see Formula 2).

Formula 1

Percentage formula

$$Percentage\ (\%) = \frac{Total\ Score}{Total\ Experts\ \times Likert\ Scale\ Points} \times 100$$

Note. This formula automatically calculates the percentage of each element.

Formula 2

Priority formula

$$Priority = IF\ (K18 >= 70, \mathrm{RANK(K18, \$K\$18{:}\ \$K\$22{,}0)})$$

Note. This formula automatically calculates the priority of each element based on the percentage result.

The condition is only true when the percentage is equal to or greater than 70%. IF(K18>=70, ⋯) is to check if the value in cell K18 (consensus percentage of the element) is equal to or greater than 70% while RANK (K18, $K$18:$K$22, 0) referred if the value is ≥70, it will rank the percentages among K18 to K22 in descending order. The "$" in the equation refers to the absolute cells that caused the range to be compared and remain the same when copied to other cells.