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Digital-integrated Chemistry Education: Assessing TPACK Profiles Through Smartphone-Based Flavonoid Analysis

Mutiara Dwi Cahyani[1], *Tania Avianda* Gusman[1*], and *Dewi* Nurdiyanti[1]

[1]Universitas Muhammadiyah Cirebon, Cirebon, Indonesia

Abstract. The integration of technology into chemistry laboratory instruction remains a challenge for pre-service teachers, particularly in achieving balanced Technological Pedagogical Content Knowledge (TPACK). Many students demonstrate strong content knowledge but struggle to integrate technological and pedagogical aspects during practical work effectively. This study aims to analyze the TPACK profiles of chemistry education students through the implementation of a green chemistry–based laboratory using an integrated Thin Layer Chromatography (TLC) box and a smartphone application to analyze flavonoid compounds from onion skin waste. A qualitative, phenomenological approach was employed to capture students' learning experiences during the practicum, supported by observation, performance assessment, and evaluation of content understanding. The results indicate that students exhibit strong content knowledge in organic chemistry and chromatographic principles, while technological and pedagogical integration remains limited and uneven. These findings suggest that green chemistry laboratories supported by mobile technology are effective for content learning but require targeted instructional scaffolding to foster balanced TPACK development.

1 Introduction

The integration of digital technologies and sustainability imperatives is transforming contemporary chemistry education. Effective instruction now requires teachers to combine subject content, pedagogical strategies, and digital tools. The Technological Pedagogical Content Knowledge (TPACK) framework [1–3] conceptualizes this integration. In laboratory environments, conceptual understanding, practical skills, and safety intersect. When teachers insufficiently integrate technology, hands-on activities may become routine procedures. This limits opportunities for inquiry-based learning that cultivates higher-order thinking and digital literacy [1].

Recent reviews indicate that TPACK research is steadily growing in science and chemistry education. These studies consistently reveal that chemistry education student

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[*] Corresponding author: tania.ag@umc.ac.id

usually demonstrate strong content knowledge, but they often lag behind or fail to connect in technological and pedagogical competencies in real laboratory settings [3,4]. For example, chemistry education student may feel confident in the subject matter but struggle to incorporate smartphone- based TLC analysis into a lesson plan. This outcome can confuse and disengage students. Studies in green chemistry education emphasize the use of safer chemicals, reducing waste, and designing laboratory activities around real-world problems [5]. These strategies aim to link chemistry with sustainability [6,7]. Smartphone-based techniques, such as imaging and colorimetric or thin-layer chromatography (TLC) analysis, provide cost-effective analytical tools [8]. Teachers' offers can turn conventional experiments into technology-enhanced activities using these methods [9]. These innovations enable educators to redesign labs for greater sustainability and digital advancement, making them more effective.

Despite these advances, three significant gaps remain. First, most researchers pursue TPACK development and green chemistry as separate goals. Few studies examine how educators integrate them in real teaching contexts [3,7]. Second, researchers show that smartphone-based tools for TLC and colorimetry perform well under controlled conditions. However, researchers provide little evidence for their effectiveness as instructional tools for pre-service teachers. In particular, it examines how well these tools help teachers integrate technical, pedagogical, and content knowledge [9]. Third, schools seldom use local and sustainable sample materials, such as flavonoid-rich onion skins, in chemistry education. Although educators find these materials relevant for both chemical analysis and green chemistry, schools rarely adopt them. Only a few studies in teacher education have combined these materials with mobile technology. Although research on TPACK, smartphone-based analytical techniques, and green chemistry has expanded in science and chemistry education, significant gaps persist because these domains are rarely integrated in authentic laboratory teaching contexts, particularly in preparing pre-service chemistry teachers to effectively connect technological, pedagogical, and content knowledge through sustainable, locally sourced materials such as flavonoid-rich onion skins.

To close these gaps, we introduce and evaluate a practical instructional design. This approach combines green-chemistry practices, such as utilizing safe solvents and upcycling onion skin waste for its flavonoid content, with an integrated TLC box for workflow efficiency. It also uses smartphone-based imaging and analysis. These features support both quantitative and qualitative interpretation of chromatography data. Teachers use technology not only for documentation but also to explore results, visualize chemical separations, and reflect on their teaching. This study examines how chemistry education students apply TPACK during a green chemistry TLC lab using smartphone-based analysis. We analyze strengths and challenges in their technical, pedagogical, and content knowledge during practical lab activities. To achieve this, we implemented a classroom-based approach in which participants extracted flavonoids from onion skins, analyzed the samples using TLC, and utilized a smartphone app to document and measure the results. Data sources included structured observations, performance rubrics for mobile-TLC use, content assessments, and analysis of student reflections. These methods aimed to capture authentic experiences and the interplay among technology, teaching practice, and content knowledge.

This study found that using mobile-assisted analytical tools in a green chemistry lab with local materials helped pre-service teachers better integrate technology with pedagogical and content knowledge (TPACK). The evidence demonstrates that technology can strengthen instructional design by making labs more sustainable and engaging and provides a model that could be applied in chemistry teacher education.

2 Method

2.1 Research design

We employed a qualitative phenomenological design to investigate how chemistry education students integrate technological, pedagogical, and content knowledge (TPACK) during a green chemistry laboratory work. We selected this design to capture authentic learning experiences and instructional decision- making as they naturally occurred in the laboratory environment, where technology use, pedagogical choices, and chemical content intersect.

2.2 Participants and learning context

Participants were chemistry education student in organic chemistry course and laboratory course and participated in this study. There were 19 chemistry students who participated in this study. We conducted the study during a scheduled laboratory session focused on analyzing organic compounds and applying principles of green chemistry. All participants completed identical tasks under uniform instructional conditions.

2.3 Materials and analytical system

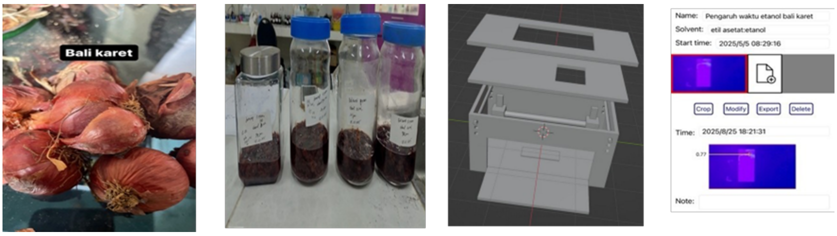
We utilized onion skin waste (Bali Karet/Sumenep variety) as a sustainable and flavonoid-rich sample. We extracted it with environmentally benign solvents, following established green chemistry protocols reported in prior studies. We performed thin-layer chromatography (TLC) using silica gel 60 F_{254} plates. An integrated TLC box combined with a smartphone-based analysis system serves as the central methodological feature. The TLC box maintains fixed illumination and camera distance to reduce variability during image acquisition. Operators

capture chromatograms using smartphone cameras (with a resolution of ≥12 MP) and process the images using a mobile application to determine Rf values and relative spot intensities.

2.4 Laboratory procedure

Flavonoids were extracted from dried onion skin waste via mild heating and filtration. Sample solutions were spotted onto TLC plates using capillary tubes with controlled volumes (±0.5 μL). Plates were developed in the integrated TLC chamber using an optimized solvent system referenced from established literature on flavonoid separation.

After development, plates were air-dried and immediately imaged using the smartphone system (**Fig. 1**).



Name: Pengaruh waktu etanol bali karet
Solvent: etil asetat:etanol
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0.77
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Fig. 1. The Flowchart of flavonoid extraction works from Bali Karet of red onion skin using certain solvents and analyzed using a thin layer chromatography box integrated with a smartphone

Qualitative analysis involved visual inspection of chromatographic separation under visible and UV light. Quantitative analysis was conducted by digital image processing through the mobile application to obtain relative intensity and Rf values. The method was intended for semi-quantitative educational analysis rather than high-precision analytical determination.

2.5 TPACK data collection

Data were collected using methodological triangulation (between-method triangulation) to enhance the robustness of qualitative finding.

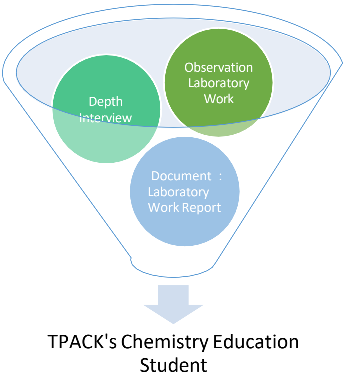

Fig. 2. Research data collection

The research phenomena were analyzed using three main qualitative methods,observation, in-depth interviews, and document analysis, running in parallel. From **Fig. 2** showed that these three data sources formed a triangulated data collection process that enables a comprehensive understanding of the TPACK profile of chemistry education students. The results of these three methods were then consolidated in the integration/convergence stage of the findings to strengthen validity and provide in-depth interpretation.

2.5.1 Observation laboratory work

To capture students' interactions with technological tools, laboratory materials, and peers. Field notes focused on indicators of technological use, pedagogical engagement, conceptual understanding, and green chemistry practices.

2.5.2 Depth interview

To explore their experiences and perceptions regarding:
a. Technology integration in laboratory learning,
b. Understanding of flavonoid analysis concepts,
c. Pedagogical reasoning and sustainability awareness.

2.5.3 Document

Documents and learning artifacts analysed included laboratory reports, student reflection journals, digital TLC images generated via the mobile application, and instructional materials used during the laboratory sessions.

2.6 Data analysis

Qualitative data were analyzed thematically using an iterative coding process aligned with the TPACK framework. Codes representing content knowledge (CK), technological knowledge (TK), pedagogical knowledge (PK), and their intersections were identified and refined. Quantitative TLC data were used as supporting evidence of students' analytical engagement and conceptual understanding rather than as primary outcome measures (**Fig. 3**).

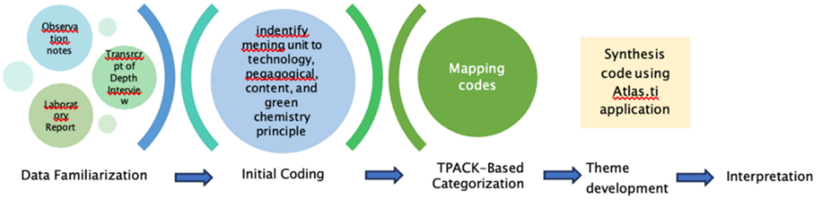

Fig. 3. Data analysis

2.7 Instrument accuracy and limitations

The smartphone-based TLC analysis system is subject to inherent limitations related to camera resolution, lens distortion, and ambient lighting conditions. Under the standardized experimental setup, the estimated uncertainty in Rf determination was ±0.02. Variability in spot intensity analysis may arise from non- uniform illumination and differences in smartphone sensor sensitivity. Consequently, the method does not provide absolute concentration values comparable to those obtained with advanced techniques such as HPLC. However, its accuracy and reproducibility are sufficient for instructional purposes, comparative analysis, and evaluation of TPACK-oriented learning.

2.8 Methodological contribution

This method offers a simplified, low-cost, and replicable approach for integrating green chemistry and mobile technology into chemistry laboratory education. By reducing dependence on advanced instrumentation while maintaining analytical relevance, the approach supports broader implementation in resource-limited educational settings. It provides a practical framework for studying TPACK development in authentic laboratory contexts.

3 Results and discussion

3.1 Results

The green chemistry laboratory activity successfully produced flavonoid extracts from onion skin waste that were suitable for Thin Layer Chromatography (TLC) analysis. Qualitative TLC results showed clear and reproducible spot separation on silica gel plates, indicating the presence of flavonoid compounds. Under visible and UV illumination, distinct chromatographic spots were consistently observed across student samples, demonstrating that the extraction and development procedures were executed correctly.

Quantitative analysis using the smartphone-based TLC system enabled digital capture and processing of chromatograms. Relative spot intensity and Rf values were successfully obtained using the mobile application. Although variations in spot intensity were observed among student groups, the overall chromatographic patterns were comparable, indicating consistent analytical outcomes. These results confirm that the integrated TLC box and mobile application were functional and reliable for semi-quantitative instructional analysis.

Performance assessment results revealed that most students were able to operate the integrated TLC box and smartphone application at a basic functional level. Students could capture chromatographic images, input data into the application, and obtain numerical outputs such as Rf values. However, differences were observed in image quality and data consistency, primarily related to camera alignment and focus during image acquisition.

Some students required repeated trials to achieve optimal image capture, indicating variability in technological proficiency. These findings suggest that while the mobile-assisted TLC system is accessible, students' technological knowledge remains uneven, particularly in optimizing digital tools for analytical purposes.

3.1.1 Observation laboratory work

Table 1 presents the mapping of observational findings to TPACK components and corresponding green chemistry practices. The results indicate that students demonstrated strong Technological Knowledge (TK), Content Knowledge (CK), and integrated TPACK through mobile-assisted TLC analysis. Pedagogical engagement was evident through collaborative inquiry; however, Pedagogical Content Knowledge (PCK) appeared less developed, as students experienced difficulty in transforming chemical concepts into explicit instructional representations. Importantly, sustainability-oriented practices—

such as waste utilization and solvent minimization—were consistently embedded within students integrated TPACK enactment.

Table 1. Results of Observation Laboratory Work

TPACK Component	Observation
TK	Students demonstrated operational mastery of digital tools that replaced more complex analytical instrument, so its more efficiency and accessibility
PK	Students discuss in group, sharing reasoning and reflective evaluation
CK	Students understand of chemical concept enabled meaningful interpretation without excessive experimental repetition
TCK	Technology supported clearer visualization of chemical phenomena, reducing trial-and-error experimentation.
TPK	Technology functioned as a pedagogical scaffold that enhanced explanation and collaboration without additional materials.
PCK	While students recognized instructional potential, explanations remained general, indicating emerging but limited PCK.
Integrated TPACK	Students integrated mobile technology, inquiry-based discussion, and flavonoid analysis within a single laboratory workflow.

3.1.2 Depth interview

Table 2. Result of Depth Interview of TPACK's Chemistry Education Students

TPACK Component	Students Answer
TK	The application makes TLC spot much clearer, so it's easier to compare the RF values without complicated tools
PK	We discussed the result together and tried explain why spots appeared differently
CK	Flavonoid move differently on the TLC plate because of their polarity, and that's why they separate
TCK	Seeing the chromatogram digitally helps me understand how polarity affects flavonoid movement
TPK	The apps help us explain the result better because everyone can clearly see the same image
PCK	I would use this experiment to show students how separation technique works in daily life but I don't know how strategy or steps to transfer the knowledge
Integrated TPACK	This laboratory work connects chemistry concept, technology and environmental awareness

The in-depth interview results show that chemistry education students demonstrated strong development in several TPACK components during green chemistry–based laboratory learning (**Table 2**). Students exhibited good Technological Knowledge (TK) through effective use of a mobile application to clarify TLC spots and compare Rf values. Pedagogical Knowledge (PK) emerged through collaborative discussions and joint interpretation of results, while Content Knowledge (CK) was reflected in students' understanding of flavonoid separation based on polarity. The integration of technology and content (TCK) and technology and pedagogy (TPK) supported clearer visualization and explanation of chromatographic results. However, Pedagogical Content Knowledge (PCK) remained limited, as students experienced difficulty translating chemical concepts into concrete instructional strategies. Overall, students recognized the practicum as an integrated experience linking chemistry concepts, technology, and environmental awareness.

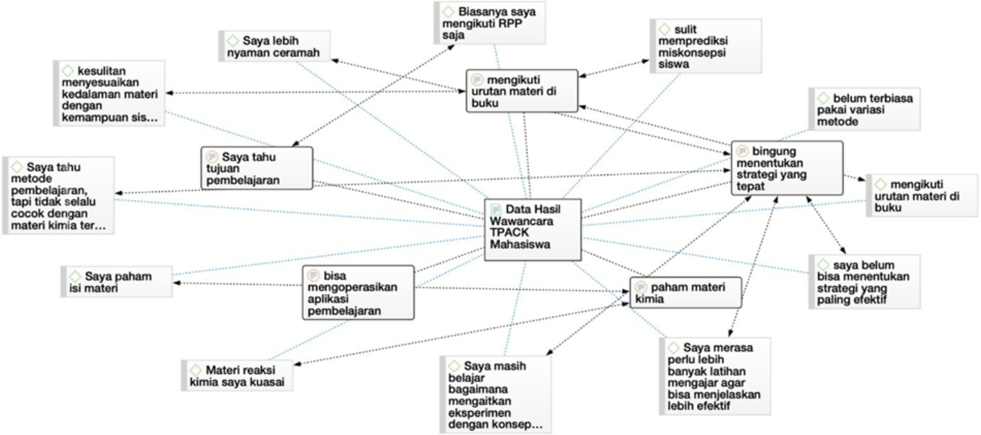

Fig. 4. Analysis data: depth interview

Based on ATLAS.ti network visualization demonstrates the formation of integrated TPACK, characterized by the convergence of mobile technology use, inquiry-based discussion. Analysis of interview data from Chemistry Education students using the Atlas.ti application revealed a pattern of code relationships indicating disparities in mastery of TPACK components, particularly in Pedagogical Content Knowledge (PCK). The code network indicates that students generally possess fairly good Content Knowledge (CK), reflected in statements such as "I understand chemistry material" and "I master chemical reactions." However, this content mastery is not accompanied by the ability to transform it into effective learning strategies (**Fig. 4**).

Codes such as "confused about determining the right strategy," "more comfortable with lectures," and "following the sequence of material in textbooks/lessons learned" indicate limitations in adaptive Pedagogical Knowledge (PK). Furthermore, the emergence of codes "difficulty predicting student misconceptions" and "difficulty adjusting the depth of material to student abilities" underscores the weakness of Associated Content Knowledge (RCK), a key element of PCK. Although students demonstrate technological literacy (TL) and the ability to operate learning applications, the integration of technology remains instrumental and is not meaningfully connected to content and pedagogy, resulting in incomplete TPK and TPACK.

Analysis of students' TPACK components indicated an imbalance among the domains. Content Knowledge (CK) emerged as the strongest component, as evidenced by accurate conceptual explanations and correct experimental execution. Technological Knowledge (TK) was moderately developed, with students able to utilize mobile analytical tools, although not always optimally. Pedagogical Knowledge (PK) appeared least developed in the laboratory context, particularly in integrating instructional strategies with experimental and technological elements.

Overall, the results demonstrate that the green chemistry laboratory supported by a mobile-assisted TLC system enabled effective chemical analysis and content learning, while simultaneously revealing gaps in technological optimization and pedagogical integration. These representative findings provide a foundation for further discussion on strengthening balanced TPACK development in chemistry teacher education.

3.2 Discussion

The present findings clarify how green chemistry–based laboratory work supported by a mobile-assisted TLC system contributes to the development of chemistry education students' TPACK. The results indicate that while students demonstrate strong content knowledge (CK) in organic chemistry and chromatographic principles, their technological knowledge (TK) and pedagogical knowledge (PK) are less consistently enacted during laboratory activities. This pattern directly addresses the research objective of examining how TPACK components emerge in an authentic practicum context, supporting earlier observations that content mastery often dominates pre-service chemistry education.

The strong CK observed in this study aligns with previous reports that chemistry education programs emphasize theoretical understanding and procedural accuracy in laboratory work [10]. Students were able to correctly explain flavonoid chemistry, solvent polarity, and TLC separation mechanisms, indicating that the green chemistry context did not compromise conceptual rigor. On the contrary, the use of onion skin waste as a sustainable analytical sample appeared to contextualize abstract concepts within a meaningful environmental narrative, reinforcing conceptual understanding rather than diluting it. This finding supports claims that green chemistry–oriented laboratories can maintain disciplinary depth while enhancing contextual relevance [10,11].

In contrast, the uneven performance in TK highlights a persistent challenge that has been reported in earlier TPACK studies. Although students successfully operated the smartphone-based TLC system at a functional level, many struggled to optimize image capture, data consistency, and digital interpretation. This suggests that access to technology alone is insufficient to foster technological competence; rather, structured pedagogical scaffolding is required to transform digital tools into epistemic instruments for learning. Similar tendencies have been reported in prior research, where mobile technologies were frequently used for documentation rather than for analytical reasoning or instructional design.

The limited enactment of PK during laboratory activities further underscores this imbalance. Observations revealed that students primarily followed procedural steps and rarely engaged in inquiry-oriented questioning or provided reflective explanations. This finding is consistent with reports that pre-service teachers often lack confidence in applying pedagogical strategies in laboratory settings, especially when simultaneously managing experimental procedures and technological tools [12]. The present results, therefore, refine previous findings by demonstrating that the introduction of mobile-assisted analytical technology, while beneficial, does not automatically strengthen pedagogical integration unless explicitly designed to do so.

Importantly, the results neither contradict nor overstate prior research but rather extend it by showing how CK, TK, and PK interact under green chemistry constraints. The findings suggest that green chemistry laboratories [13] can serve as effective platforms for TPACK development, provided that instructional design explicitly foregrounds pedagogical reasoning and technological purpose. The observed gaps do not indicate failure of the method but instead reveal where targeted intervention is needed—particularly in aligning mobile technology use with pedagogical intent.

It is strategically relevant to the implementation of the Kurikulum merdeka in chemistry learning in high schools due to the emphasis of project-based, contextual, and listening learning on mastering 21st-century competencies and the Pancasila Student Profile, especially critical reasoning, creativity, and environmental awareness. The integrated analysis of flavonoids from Balinese rubber onion waste using a TLC box integrated with a smartphone application represents a differentiated and exploration-based learning practice that aligns with the student-centered learning principles in the Kurikulum Merdeka, while supporting elements of sustainable development and digital literacy. The findings of this study imply that the curriculum for prospective chemistry teachers needs to explicitly integrate TPACK outcomes with green chemistry project-based learning designs and mobile technology, so that prospective teachers not only master the concepts of compound analysis and chromatography, but are also able to transform them into meaningful learning based on local problems in high schools [14]. Therefore, strengthening the curriculum structure of LPTK should include innovative courses or practical modules integrated with green chemistry [15], authentic project-based assessments, and the use of simple yet applicable technology, so that the implementation of the Independent Curriculum in schools is truly supported by the pedagogical, technological, and ecological readiness of future chemistry teachers.

From a methodological perspective, the use of a simplified, smartphone- based TLC system demonstrates that meaningful analytical experiences can be achieved without the need for advanced instrumentation [15]. While the method does not offer the precision of techniques such as HPLC, its semi-quantitative capability proved sufficient to support conceptual understanding and comparative analysis. This trade-off between analytical precision and pedagogical accessibility represents a deliberate design choice rather than a limitation, aligning with the educational goals of the study.

Several limitations must be acknowledged. The phenomenological design prioritizes depth of experience over generalizability, resulting in findings that are context-dependent. Additionally, technological performance may have been influenced by variations in smartphone hardware. Future studies could address these limitations by incorporating mixed-method designs, controlled comparisons with conventional analytical tools, or longitudinal tracking of TPACK development.

Overall, the novelty of this study lies not in introducing a new analytical technique, but in demonstrating how a low-cost, green chemistry–oriented laboratory design can expose latent imbalances within TPACK. By making imbalances visible, the study provides a practical basis for refining chemistry teacher education curricula to better integrate technology, pedagogy, and content in sustainable laboratory instruction.

4 Conclusion

This study demonstrates that green chemistry–based laboratory instruction supported by an integrated TLC box and smartphone application provides a meaningful context for examining the development of Technological Pedagogical Content Knowledge (TPACK) among chemistry education students. The findings indicate that while students possess strong content knowledge in organic chemistry and chromatographic principles, the integration of technological and pedagogical knowledge remains uneven during laboratory practice. The use of onion skin waste as a sustainable analytical sample successfully preserved conceptual rigor while reinforcing environmental relevance, confirming that green chemistry contexts can support both disciplinary understanding and instructional authenticity. Importantly, the results reveal that the primary contribution of this work lies in making TPACK imbalances visible within an authentic laboratory setting. The mobile-assisted TLC approach functioned effectively as a low-cost and accessible analytical tool, yet its pedagogical potential was not fully realized without explicit instructional scaffolding. These insights suggest that future chemistry teacher education should move beyond introducing technology as a tool and instead emphasize its purposeful alignment with pedagogy and content.

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