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μPADs for Chemistry Education and Acetic Acid Analysis: A Literature Review

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Abstract
Microfluidic paper-based analytical devices (μPADs) have emerged as promising analytical platforms due to their low cost, portability, simplicity, and minimal reagent requirements. These characteristics make μPADs attractive for both chemical analysis and chemistry education, particularly in laboratory activities that emphasize sustainable and environmentally friendly practices. This literature review aims to examine the development and application of μPADs in chemistry learning and acetic acid determination through acid–base titration experiments. A descriptive literature review with a qualitative approach was conducted using articles published between 2016 and 2025. Relevant literature was identified through Google Scholar, ScienceDirect, PubMed, and ACS Publications using keywords related to μPADs, chemistry education, acid–base titration, and acetic acid analysis. Following a screening and eligibility assessment process, 21 peer-reviewed articles were selected and analyzed using qualitative content analysis. The findings indicate that μPADs serve not only as analytical tools but also as instructional media that support the understanding of acid–base reactions, stoichiometry, limiting reagents, and titration concepts through microscale experimentation. In acetic acid analysis, distance-based and colorimetric μPADs integrated with smartphone-assisted image processing provide results comparable to conventional titration methods while reducing reagent consumption, analysis time, and chemical waste generation. The integration of digital image analysis also introduces students to modern analytical techniques and enhances digital literacy skills. Despite challenges related to fabrication standardization and analytical reproducibility, μPADs demonstrate considerable potential for implementation in higher education laboratories as cost-effective and sustainable tools that support green analytical chemistry practices.

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INTRODUCTION

The development of chemical analysis technology increasingly emphasizes approaches that are efficient, environmentally friendly, and easily applicable in various contexts, including education (Mazwan et al., 2024). However, in practice, many conventional analytical methods, including acid–base titration, still rely on relatively complex laboratory equipment, the use of large reagent volumes, and lengthy analysis times (Dias et al., 2023).

This condition poses particular challenges, especially in educational laboratory settings and institutions with limited facilities, thereby necessitating alternative analytical methods that are simpler and more sustainable (Namwong et al., 2018). One rapidly developing approach to address these challenges is the use of microfluidic paper-based analytical devices (μPADs) (Anggraini, 2016). Since they were first introduced by George M. Whitesides in 2007, μPADs have attracted widespread attention due to their low cost, portability, and ability to perform chemical analyses using very small reagent volumes (Damayanti, 2019). The use of paper as the primary substrate enables the analytical process to occur passively through capillary action, thereby eliminating the need for complex additional instrumentation (Kuna, 2023).

In the field of chemical analysis, μPADs have been widely applied for various purposes, ranging from simple titrations based on color indicators, determination of limiting reagents, to the analysis of specific compounds and ions in environmental samples and commercial products (Dona et al., 2024; Nogueira et al., 2017; Sulistyarti et al., 2021). In particular, several studies have demonstrated that μPADs show promising potential for acetic acid analysis through an acid–base titration approach based on indicator color changes, with accuracy comparable to conventional methods (Wisang et al., 2019).

Recent developments also indicate the integration of μPADs with modern analytical approaches, such as digital image processing and the application of the CIE L*a*b* color system to enhance the precision of quantitative analysis results (Komatsu et al., 2016). Design innovations, including the development of three-dimensional μPADs and origami-based approaches, have further expanded the application of these devices in various analytical contexts (Almeida et al., 2018). Nevertheless, most of these studies still focus primarily on the technical aspects and analytical performance of μPADs, with emphasis on method development and validation of measurement results.

Despite the growing number of studies on microfluidic paper-based analytical devices (μPADs), the available literature remains fragmented across different application areas, including environmental monitoring, food analysis, medical diagnostics, and chemical education. Most studies focus on the technical development and analytical performance of μPADs, whereas their potential integration into educational laboratory activities, particularly for acetic acid determination through acid–base titration, has received less comprehensive attention. This topic was selected because acetic acid analysis is one of the most common experiments in chemistry laboratories, while μPADs offer a promising alternative that supports low-cost experimentation, reduced chemical consumption, and green chemistry principles. Furthermore, a comprehensive review is needed to synthesize existing findings, evaluate current research trends, and identify opportunities for integrating μPAD-based analytical methods into chemistry education. Such a review may provide valuable insights for researchers and educators seeking sustainable and innovative laboratory practices.

To date, studies specifically highlighting the utilization of μPADs for acetic acid analysis within the context of educational laboratory experiments remain relatively limited. In fact, this approach has the potential not only to provide a more cost-effective and environmentally friendly analytical method, but also to align with green chemistry principles that are increasingly emphasized in the development of modern chemistry laboratory practices. This limited comprehensive investigation reveals a research gap regarding how μPADs can be optimally developed and implemented as an efficient and sustainable solution for acetic acid analysis in laboratory activities.

Based on this background, this article aims to present a systematic literature reflection on the development and application of μPADs in chemical analysis, with a particular focus on acid–base titration experiments for determining acetic acid content. This review is expected to provide an overview of the state of the art, identify opportunities for further development, and serve as a scientific foundation for advancing analytical methods that are efficient, accurate, and oriented toward green chemistry principles within the context of educational laboratories.

METHOD

This study employed a descriptive literature review with a qualitative approach to examine the development and application of microfluidic paper-based analytical devices (μPADs) in chemistry education and acetic acid analysis. The review aimed to identify research trends, summarize major findings, and explore research gaps related to the implementation of μPADs in acid–base titration experiments and green chemistry-based laboratory learning. Although a systematic search procedure was applied, this study focused on descriptive synthesis and interpretation of previous findings rather than following the full protocol of a systematic literature review or scoping review.

The literature search was conducted between January and March 2025 using several academic databases, including Google Scholar, ScienceDirect, PubMed, and ACS Publications. The search employed combinations of keywords and Boolean operators, such as "μPAD" AND "acid–base titration", "microfluidic paper-based analytical device" AND "chemistry education", "μPAD" AND "acetic acid analysis", and "paper-based analytical device" AND "green chemistry". The inclusion criteria comprised peer-reviewed articles published between 2016 and 2025, studies related to μPAD applications in chemistry education or chemical analysis, and articles written in English or Indonesian. Articles were excluded if they were duplicates, conference abstracts without full-text access, unrelated to the research focus, or contained incomplete methodological information.

The initial search yielded 26 articles. After the removal of one duplicate article, 25 articles remained for title and abstract screening. Three articles were excluded because they were not directly related to the application of μPADs in chemistry education or acetic acid analysis. The remaining 22 articles underwent full-text assessment, and one article was excluded due to insufficient methodological information. Consequently, 21 articles were included in the final analysis, consisting of 17 articles discussing the development and implementation of μPADs in acid–base titration and chemistry learning, and four articles focusing on acetic acid determination.

Data extraction was conducted using a literature review matrix containing information on publication year, research objectives, fabrication methods, analytical techniques, major findings, and educational implications. The selected articles were analyzed by qualitative content analysis to identify patterns, similarities, differences, and emerging research trends. To ensure the credibility and quality of the reviewed studies, each article was evaluated based on methodological clarity, relevance to the research objectives, completeness of analytical procedures, and consistency of the reported findings. The synthesized results were then organized systematically to provide an overview of the current state of research and future opportunities for implementing μPADs in sustainable and environmentally friendly chemistry laboratory education.

RESULTS AND DISCUSSION

Result

The utilization of microfluidic paper-based analytical devices (μPADs) in chemistry education and acetic acid content analysis has shown rapid development over the past decade. Based on a review of 21 relevant scientific articles published between 2016 and 2025, μPADs have proven to be effective both as simple analytical tools and as instructional media that support the understanding of abstract chemical concepts.

Table 1. Review Findings

Title	Review Findings	References
Developments Of Microfluidic Paper-Based Analytical Devices (Mpads) For Water Analysis: a Review	μPADs are sensitive to various analytes (such as nitrite, phosphate, and heavy metals), while remaining low-cost and environmentally friendly.	(Almeida et al., 2018)
Microfluidic Paper-Based Analytical Device (μPAD) For Determining Hydroquinone in Facial Whitening Cream using Phloroglucinol Reagent	μPADs detect hydroquinone accurately and stably using a colorimetric method.	(Sulistyarti et al., 2021)
Image Analysis For a Microfluidic Paper-Based Analytical Device using the CIE L* a* b* Color System	pH analysis using μPADs based on CIE L*a*b* digital image processing without additional laboratory instruments.	(Komatsu et al., 2016)
Review On Microfluidic Paper-Based Analytical Devices Towards Commercialisation	Modern μPAD fabrication methods (such as laser cutting, inkjet printing, and screen printing) enhance analytical accuracy and commercialization potential.	(Akyazi et al., 2018)
Microfluidic Paper-based Analytical Devices (μPADs) For Analysis Lead Using Naked Eye and Colorimetric Detections	μPADs visually detect Pb(II) ions with high sensitivity at low cost.	(Wisang et al, 2019)

Title	Review Findings	References
Paper-Based Inkjet-Printed Microfluidic Analytical Devices	Inkjet printing technology enables the fabrication of multifunctional μPADs with high precision and reusability.	(Yamada et al., 2015)
Colorimetric Paper-Based Analytical Device Coupled With Hollow Fiber Membrane Liquid Phase Microextraction (HF-LPME) For Highly Sensitive Detection of Hexavalent Chromium in Water Samples	The combination of μPADs and membrane extraction enables the detection of Cr(VI) with high sensitivity and good precision.	(Alahmad et al., 2018)
Recent advances in microfluidic paper-based analytical devices toward high-throughput screening	μPADs are low-cost, portable, and promising tools for high-throughput screening in healthcare, environmental, and food analysis. Despite existing challenges, their future potential remains significant.	(Boobphahom et al., 2020)
Monitoring Acid–Base Titrations On Wax Printed Paper Microzones using a Smartphone	μPADs are capable of determining acetic acid content with results comparable to conventional titration.	(Nogueira et al., 2017)
Fabricating Simple Wax Screen-Printing Paper-Based Analytical Devices To Demonstrate the Concept of Limiting Reagent in Acid–Base Reactions	μPADs effectively explain the concept of limiting reagents in a visual and efficient manner.	(Namwong et al., 2018)
Penentuan Kadar Asam Asetat Dalam Larutan Cuka Makan Yang Beredar Di Pekanbaru Dengan Metode Alkalimetri	There is a variation in acetic acid content ranging from 1.47% to 24.79%, indicating the need for new and rapid methods to analyze acetic acid levels in a simpler manner.	(Dona et al., 2024)
Penetapan Kadar Produk Makanan Asam Cuka (CH_3COOH) Yang Beredar Dipasaran	Conventional titration is sufficiently accurate, however, it requires a longer time and larger amounts of chemicals.	(Kuna, 2023)
Paper-Based Analytical Devices For Environmental Analysis	μPADs are effective for environmental monitoring, providing results comparable to laboratory-based methods.	(Meredith et al., 2016)
Microfluidic Paper-Based Analytical Devices: From Design To Applications	μPADs are widely applied in diagnostics, food analysis, and education, featuring innovative three-dimensional designs.	(Noviana et al., 2021)
Fabrication of a Paper-Based Microfluidic Device Using a Simple Method for Chemical Analysis	Simple fabrication methods make μPADs suitable for basic chemistry experimental learning.	(Sokpheak et al., 2024)
Recent Advances in the Application of Microfluidic Paper-Based Devices for Environment Sample Analysis	μPADs are efficient, environmentally friendly, and relevant for environmental chemistry education.	(Mulu et al., 2024)
Microfluidic Paper-Based Sensors and Their Applications for Glucose Sensing	The integration of digital sensors with μPADs has the potential to advance toward AI-based automated analysis.	(Le & Cho, 2025)
Advances in Microfluidic Paper-Based Analytical Devices (μPADs): Design, Fabrication, and Applications	Nanotechnology-based innovations enhance the sensitivity and response speed of μPADs.	(Chen et al., 2024)
Product design: Microfluidic paper-based analytical device	μPAD design supports quantitative analysis and the learning of chemical techniques.	(Lawrence et al., 2025)
Microfluidic paper analytic device (μPAD) technology for food safety applications	μPADs are capable of detecting food contaminants rapidly, at low cost, and in an environmentally friendly manner.	(Samon et al., 2024)
Two mechanisms for acetic acid synthesis from ethanol and water	Explains the fundamental formation of acetic acid as the main analyte in chemical analysis.	(Gonzalez et al., 2019)

Based on the table, the utilization of microfluidic paper-based analytical devices (μPADs) in chemistry education and the determination of acetic acid content has shown significant development over the past decade. μPADs utilize the natural capillary action of paper fibers to transport solutions without requiring external power sources, making them ideal for educational laboratories, particularly in regions with limited facilities (Jarujamrus et al., 2020).

The Role of μPADs in Chemistry Learning

μPADs play an important role in chemistry learning because they help students understand abstract chemical concepts through direct experimentation and visualization of chemical reactions. The use of color indicators in μPADs allows students to observe color changes during acid–base titration processes more clearly and simply (Komatsu et al., 2016; Nogueira et al., 2017). In particular, the implementation of paper-based micro acid–base titration has been proven effective in training undergraduate students in nutrition education to understand practical chemical analysis interactively (Huang & Cai, 2022). In addition, μPADs support the understanding of pH, stoichiometry, and limiting reagent concepts through interactive microscale experiments.

Namwong et al. (2018) demonstrated that wax screen-printing-based μPADs effectively explain the concept of limiting reagents in acid–base reactions visually. Yamada et al. (2015) also reported that inkjet printing technology enables the fabrication of highly precise μPADs, making them highly suitable for educational laboratory activities. Due to their simple and portable characteristics, μPADs can increase student engagement in experiment-based learning (Sokpheak et al., 2024).

Previous finding is supported by Lawrence et al. (2025), who stated that μPAD design supports the learning of analytical chemistry techniques more effectively. Furthermore, Gonzalez et al. (2019) explained the mechanism of acetic acid formation, which can strengthen conceptual understanding in acid–base analysis experiments using μPADs. Therefore, μPADs function not only as analytical tools but also as instructional media that improve students' conceptual understanding and laboratory skills.

Advantages of μPADs Compared to Conventional Titration

Compared with conventional titration methods, μPADs offer several practical and economic advantages. μPADs require only microliter-scale reagent volumes, significantly reducing chemical consumption (Dias et al., 2023; Xu et al., 2024). For example, these paper-based analytical devices are capable of manipulating extremely small sample volumes ranging from 10^{-9} to 10^{-18} liters within micrometer-scale channels, dramatically accelerating mixing and chemical reaction processes (Boobphahom et al., 2020). In addition, the analytical process is faster because solution transport occurs naturally through capillary action without requiring complex additional instruments (Jarujamrus et al., 2020). The inherent advantage of paper usage lies in its natural capillary action, which enables self-driven fluid flow without the need for external pumps or additional power sources (Erkocyigit et al., 2023; Lim et al., 2019). The reduction in reagent usage also decreases chemical waste generation, resulting in lower laboratory operational costs. From a safety perspective, μPADs are safer because students are exposed to smaller amounts of hazardous chemicals. Nogueira et al. (2017) demonstrated that μPADs can determine acetic acid content with results comparable to conventional titration methods while requiring shorter analysis time and lower reagent volumes. Kuna (2023) also emphasized that conventional titration requires longer analysis time and larger reagent volumes compared with μPAD-based methods. Dona et al. (2024) further reported variations in acetic acid content in commercial vinegar products, highlighting the need for rapid and efficient analytical methods such as μPADs. Therefore, μPADs represent a more economical, practical, and efficient alternative for laboratory analysis and chemistry practical activities.

Suitability of μPADs with Green Chemistry Principles

The use of μPADs strongly aligns with green chemistry principles because they support waste reduction, efficient chemical usage, and safer experimental procedures. μPADs utilize paper as the primary substrate, which is biodegradable, disposable, and environmentally friendly (Almeida et al., 2018; Mulu et al., 2024). Their environmentally friendly characteristics make them an ideal green analytical methodology for large-scale field testing, such as detecting adulteration in automotive urea products with minimal environmental impact (Souza et al., 2022). Moreover, experiments are conducted on a microscale, significantly minimizing reagent consumption and chemical waste production (Dias et al., 2023). Meredith et al. (2016) stated that μPADs are highly effective for environmental analysis because they produce less waste than conventional laboratory methods. The use of simple equipment and low energy consumption also makes μPADs safer and more economical for educational laboratories. Samon et al. (2024) additionally reported that μPADs in food safety applications can rapidly detect contaminants at low cost with minimal environmental impact. Furthermore, Mulu et al. (2024) explained that μPADs are highly relevant for environmental chemistry education because they support efficient and sustainable experimentation. Therefore, the implementation of μPADs represents a practical application of green analytical chemistry principles in higher education laboratories.

Integration of Digital Image Processing in μPADs

The development of μPADs has advanced significantly through the integration of digital image processing technologies using smartphones and color analysis systems. Smartphones are used to capture images of color reactions on μPADs, and the resulting colors are analyzed using RGB parameters or the CIE Lab* color system (Komatsu et al., 2016). The use of the CIE Lab* system improves analytical objectivity because color changes can be quantitatively measured rather than relying solely on subjective visual observation. Nogueira et al. (2017) also utilized the smartphone-based Photometrix® application to accurately determine acetic acid content through color analysis on μPADs. In addition to improving analytical quality, smartphone integration introduces students to modern digital technologies in chemistry laboratories. This smartphone-based mobile detection system not only facilitates advanced point-of-care diagnostics but also enables the conversion of colorimetric reaction results into digital data (Erkocyigit et al., 2023; Lim et al., 2019). The integration of digital technology can even be associated with QR codes or barcodes for future information storage within cloud computing systems (Boobphahom et al., 2020). Le and Cho (2025) stated that the integration of digital sensors with μPADs has the potential to support future artificial intelligence (AI)-based automated analysis systems. Chen et al. (2024) also explained that nanotechnology innovations can improve the sensitivity of μPAD-based detection systems, resulting in faster and more precise analytical performance. Therefore, the integration of digital image processing not only enhances the analytical accuracy of μPADs but also supports the development of students' digital literacy in modern chemistry education.

Limitations of μPADs Applications

Despite their many advantages, μPADs still possess several limitations that must be considered. Color-based analysis is highly influenced by lighting conditions during image acquisition, causing analytical results to vary if illumination intensity is inconsistent (Komatsu et al., 2016). In addition, differences in paper type, pore structure, and microfluidic channel design can affect fluid flow behavior and analytical consistency (Akyazi et al., 2018; Noviana et al., 2021). Environmental humidity may also influence reagent stability and color development on paper surfaces. Furthermore, color uniformity in the detection zone is often disrupted by solute-to-surface interactions along the analytical channels, which can trigger the coffee-ring effect or washing effect, thereby reducing the sensitivity and stability of test results (Musile et al., 2023). Reproducibility remains a challenge because manual fabrication processes can produce variations among devices. Chen et al. (2024) explained that improvements in μPAD sensitivity and stability are still being developed through nanotechnology approaches. Furthermore, Sokpheak et al. (2024) stated that simple fabrication methods must be accompanied by proper standardization to ensure more consistent analytical results. Therefore, further research is still needed to improve calibration systems, device stability, and fabrication consistency so that μPADs can be more widely implemented in chemistry analysis and education.

Implications of μPADs for Higher Education

μPADs have strong potential to be integrated into Basic Chemistry, Analytical Chemistry, and Environmental Chemistry laboratory courses in higher education. In Basic Chemistry laboratories, μPADs can be used to study acid–base concepts, indicators, stoichiometry, and titration in a simpler and safer manner (Namwong et al., 2018).

In Analytical Chemistry, students can learn quantitative analysis, digital image processing, and colorimetric techniques using inexpensive and easily fabricated devices (Komatsu et al., 2016; Nogueira et al., 2017). Meanwhile, in Environmental Chemistry, μPADs can be applied for rapid and portable water quality analysis and environmental contaminant detection (Almeida et al., 2018; Meredith et al., 2016; Mulu et al., 2024). Through these multidisciplinary experiments, students can be introduced to the broad real-world applications of μPADs, ranging from disease biomarker screening and food/beverage quality control to their applications in clinical and forensic toxicology for rapid on-site detection of toxic substances or illicit drugs (Boobphahom et al., 2020; Erkocyigit et al., 2023; Musile et al., 2023). The low cost, simplicity, and environmentally friendly characteristics of μPADs make them highly suitable for educational institutions with limited laboratory facilities (Sokpheak et al., 2024). Lawrence et al. (2025) also emphasized that μPAD design supports innovative and application-based analytical chemistry learning. In addition to improving students' laboratory skills, the implementation of μPADs also supports technology-based learning, sustainable laboratory culture, and the integration of green chemistry principles in higher education.

Discussion

The findings of this review indicate that μPADs have substantial potential to transform chemistry laboratory practices by providing analytical performance comparable to conventional titration while significantly reducing reagent consumption and chemical waste. This finding supports the growing emphasis on green analytical chemistry, where sustainability and efficiency are becoming central considerations in laboratory instruction. Beyond their analytical function, μPADs also offer important pedagogical benefits. Their visual and microscale characteristics enable students to directly observe chemical phenomena that are often difficult to understand through theoretical instruction alone, thereby supporting meaningful learning and conceptual understanding of acid–base reactions, stoichiometry, and limiting reagents.

The integration of smartphone-based image analysis further extends the educational value of μPADs by introducing students to digital analytical techniques commonly used in modern chemistry. Such integration promotes digital literacy and data interpretation skills while increasing measurement objectivity. However, several challenges remain, including the influence of lighting conditions, variations in paper substrates, and the lack of standardized fabrication procedures, all of which may affect analytical reproducibility. In addition, although numerous studies have investigated the analytical performance of μPADs, relatively few have evaluated their impact on student learning outcomes. This represents an important research gap, particularly in the context of acetic acid determination experiments, which remain among the most common laboratory activities in chemistry education.

CONCLUSION

This literature review demonstrates that microfluidic paper-based analytical devices (μPADs) represent a promising innovation for both chemistry education and acetic acid analysis. Based on the synthesis of 21 scientific articles published between 2016 and 2025, μPADs have evolved from simple paper-based analytical platforms into multifunctional tools that support quantitative chemical analysis, digital integration, and student-centered laboratory learning

The reviewed studies indicate that μPADs can determine acetic acid content with analytical performance comparable to conventional acid–base titration while requiring substantially lower reagent volumes, shorter analysis times, and generating less chemical waste. These characteristics make μPADs consistent with the principles of green analytical chemistry and suitable for sustainable laboratory practices. From an educational perspective, μPADs facilitate the visualization of abstract chemistry concepts, including acid–base reactions, stoichiometry, limiting reagents, and titration processes, through interactive microscale experiments.

The integration of smartphone-based image analysis further enhances learning by introducing students to digital analytical techniques and data interpretation skills relevant to modern chemistry laboratories.

Despite challenges related to analytical reproducibility, fabrication standardization, and environmental influences on colorimetric measurements, the overall evidence suggests that μPADs possess considerable potential for implementation in higher education laboratories. Future research should focus on developing standardized fabrication protocols, improving analytical reliability, and empirically evaluating the impact of μPAD-based experiments on students' conceptual understanding, laboratory competencies, and green chemistry awareness. Overall, μPADs offer an effective, economical, and environmentally responsible alternative for advancing chemistry education and acetic acid analysis in the context of sustainable laboratory innovation.

RECOMMENDATION

μPADs are highly suitable for higher education institutions with limited laboratory facilities, as they require minimal equipment and low operational costs. The integration of μPADs with digital image processing further opens opportunities for modernizing laboratory instruction and fostering data-driven analytical skills. Therefore, chemistry educators are encouraged to incorporate μPAD-based experiments into acid–base titration modules to promote contextual and sustainable learning, while curriculum developers may embed green analytical chemistry principles through their implementation in laboratory courses. Future studies should empirically evaluate learning outcomes, analytical accuracy under standardized conditions, and long-term pedagogical impacts. Additionally, the development of standardized protocols and lighting calibration guidelines is recommended to improve the reproducibility and reliability of quantitative results. These recommendations are particularly relevant for higher education institutions, laboratory instructors, and chemistry education researchers aiming to design cost-effective, environmentally friendly, and pedagogically meaningful laboratory innovations.

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