Diversitas Journal
ISSN 2525-5215
Volume 10, Issue 3 (Jul./Sep. 2025) p. 3519 – 1344
https://diversitasjournal.com.br/diversitas_journal

Advancing Agricultural Forensics through Pedagogical Innovation: Development of a Training Module on Machine Learning-assisted Ubi "Kinampay" Geographic Origin Differentiation

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ABSTRACT

The growing emphasis on food traceability and authenticity has heightened the demand for advanced analytical techniques capable of verifying both the geographic origin and varietal identity of premium crops. In the Philippine context, ubi 'Kinampay' (*Dioscorea alata* L.) is regarded as a culturally significant and economically valuable commodity, yet remains susceptible to misidentification and economically motivated fraud. Although methods such as X-ray fluorescence (XRF) and stable isotope analysis present viable solutions for forensic verification, their adoption is hindered by the scarcity of skilled practitioners and the absence of formalized training programs. This study responds to that need through the design and evaluation of a competency-based training module tailored for science professionals working in nuclear forensic applications related to agriculture. Drawing on the principles of Mezirow's Transformative Learning Theory and Kolb's Experiential Learning Cycle, the training integrates adult learning pedagogies with domain-specific content. A mixed-method developmental research design was employed, combining expert validation via Likert-scale assessment with qualitative insights obtained through thematic analysis of interviews. Results showed consistent strong agreement across key dimensions, including content coherence, instructional design, visual aids, and science identity reinforcement. Qualitative data further emphasized the module's clarity, scientific accuracy, and relevance to professional practice, while also noting the need for refinements in cognitive load and interface usability. Overall, the module demonstrates both pedagogical soundness and technical validity, positioning it as a scalable solution for institutional capacity-building in agricultural traceability. Strategic recommendations focus on module enhancement and alignment with policy frameworks such as Geographical Indication (GI) protection.

ARTICLE INFORMATION

Article process:
Submitted: 07/06/2025
Approved: 09/23/2025
Published: 10/06/2025

Keywords:
Food Authenticity, Geographic Origin, Isotope Analysis, Competency-Based Training, Agricultural Traceability, Ubi, Machine Learning

RESUMO

A crescente ênfase na rastreabilidade e autenticidade dos alimentos aumentou a demanda por técnicas analíticas avançadas capazes de verificar tanto a origem geográfica quanto a identidade varietal de culturas agrícolas premium. No contexto filipino, o ubi 'Kinampay' (*Dioscorea alata L.*) é considerado uma mercadoria de grande valor cultural e econômico, mas permanece suscetível à identificação incorreta e a fraudes motivadas economicamente. Embora métodos como fluorescência de raios X (XRF) e análise de isótopos estáveis ofereçam soluções viáveis para verificação forense, sua adoção é limitada pela escassez de profissionais qualificados e pela ausência de programas formais de treinamento. Este estudo responde a essa necessidade por meio do desenvolvimento e avaliação de um módulo de treinamento baseado em competências, voltado para profissionais da ciência que atuam em aplicações forenses nucleares relacionadas à agricultura. Com base nos princípios da Teoria da Aprendizagem Transformadora de Mezirow e no Ciclo de Aprendizagem Experiencial de Kolb, o treinamento integra pedagogias da educação de adultos com conteúdo específicos da área. Um desenho de pesquisa desenvolvimental de métodos mistos foi empregado, combinando validação por especialistas por meio de avaliação em escala Likert com percepções qualitativas obtidas por análise temática de entrevistas. Os resultados mostraram concordância forte e consistente em dimensões-chave, incluindo coerência do conteúdo, design instrucional, recursos visuais e reforço da identidade científica. Os dados qualitativos enfatizaram ainda a clareza do módulo, sua precisão científica e relevância para a prática profissional, ao mesmo tempo em que apontaram a necessidade de ajustes na carga cognitiva e na usabilidade da interface. No geral, o módulo demonstra solidez pedagógica e validade técnica, posicionando-se como uma solução escalável para o fortalecimento institucional da rastreabilidade agrícola. As recomendações estratégicas concentram-se no aprimoramento do módulo e na sua harmonização com marcos políticos como a proteção por Indicação Geográfica (IG).

Keywords:
Autenticidade dos Alimentos, Origem Geográfica, Análise de Isótopos, Treinamento Baseado em Competências, Rastreabilidade Agrícola, Ubi, Aprendizado de Máquina

DOI: 10.48017/dj.v10i3.3519

Introduction

The increasing global demand for food authenticity and traceability has made the accurate geographic and varietal identification of high-value crops an imperative in agri-food systems. In the Philippines, Dioscorea alata L., locally known as ubi, holds both economic and cultural significance, especially in the province of Bohol where the “Kinampay” variety is esteemed for its sensory and culinary qualities. As ubi “Kinampay” continues to gain market value, particularly in domestic and diaspora markets, concerns over varietal misrepresentation, substitution, and fraudulent labeling have intensified—threatening not only market integrity but also the livelihood of smallholder farmers and the cultural heritage attached to the crop.

Scientific tools such as X-ray fluorescence (XRF) elemental profiling and stable isotope analysis are increasingly being applied to resolve such issues of origin authentication and varietal differentiation (PNRI, 2021). These techniques offer high-resolution, instrument-based evidence to detect product mislabeling and adulteration, thus supporting compliance with food safety legislation such as the Philippine Food Safety Act of 2013. Additionally, they provide a technical foundation for the potential registration of ubi “Kinampay” as a Geographical Indication (GI) product, which would further elevate its competitiveness in global markets.

Despite the promise of these technologies, their effective use in the Philippine agricultural context is constrained by a shortage of trained professionals and the absence of structured training programs tailored to isotope and elemental-based geographic traceability. Previous capacity-building initiatives, such as those led by the Philippine Nuclear Research Institute (PNRI) and its international partners, have underscored the strategic role of technical training in enhancing local analytical capabilities (FAO-IAEA, 2021). However, these efforts remain fragmented and insufficient to support the broader goal of institutionalizing forensic traceability in agricultural systems.

This study addresses this critical gap by designing and evaluating a modular training program specifically focused on geographic and varietal differentiation of ubi “Kinampay”. Anchored in contemporary pedagogical frameworks, the module development is informed by literature on adult technical education, digital and hybrid instructional modalities, and competency-based training systems (Dembitska et al., 2023; Chsherbakova, 2024). The training design incorporates simulation-based learning, hands-on laboratory exposure, and reflective assessment methods to ensure relevance, adaptability, and rigor in content delivery (Trubitsyn & Kalmykova, 2023; Jensen, 2015).

To validate the technical and pedagogical dimensions of the module, the study employed a two-phase evaluation: (1) a Likert-based expert assessment of module criteria and content; and (2) semi-structured interviews to extract qualitative insights, enabling deeper thematic analysis of strengths, gaps, and future directions. This design not only ensures content validity but also positions the training module as a replicable model for capacitating science professionals in agricultural traceability using nuclear and isotope techniques.

Framework

The Competency-Based Continuing Professional Development (CPD) framework offers a robust model for structuring professional education grounded in dynamic skill acquisition rather than static qualifications. It reconceptualizes competence as a continuous, context-driven progression toward expertise, emphasizing defined learning outcomes that enable professionals to identify learning needs, formulate practice-relevant questions, access emerging sources of knowledge, and evaluate their competence and performance (Frank et al., 2010; Holmboe et al., 2018).

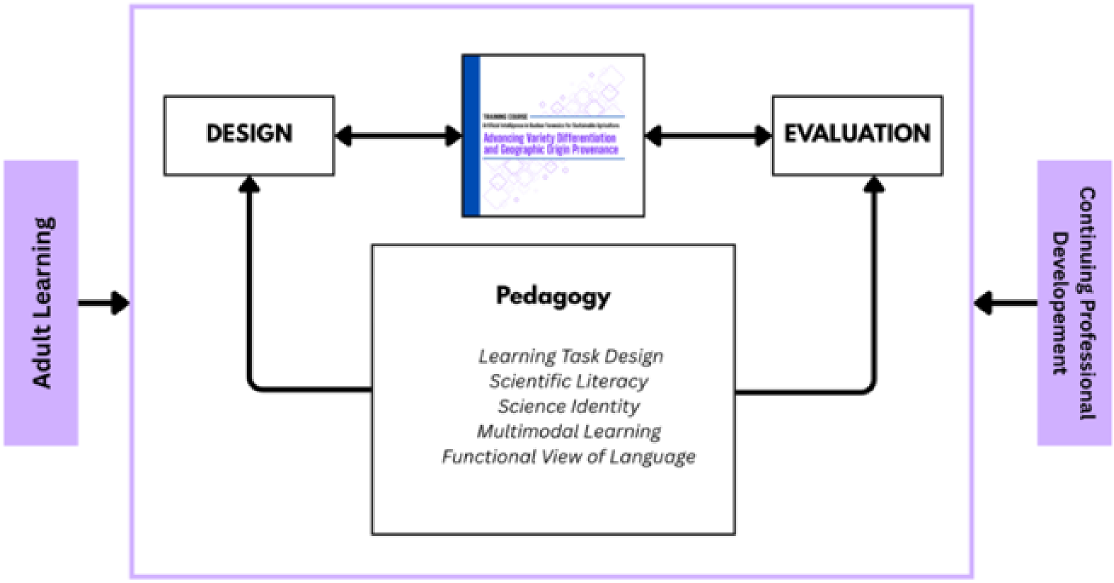
Central to this framework are principles of self-directed learning and reflective assessment, positioning ongoing evaluation not merely as a pedagogical function but as a core professional obligation (Moineau et al., 2010). Despite its potential, implementing a competency-based CPD system presents challenges, including the articulation of measurable competencies and the establishment of scalable monitoring and feedback mechanisms (Gruppen et al., 2018). The framework also calls for cultivating learning engagement across disciplinary boundaries and ensuring that professionals adapt to evolving demands in their fields. In the context of healthcare, such approaches have been linked to improved practitioner performance, higher quality of service, and enhanced patient safety (Murray et al., 2020).

This conceptual foundation (Figure 1) is equally applicable to the development of training programs for science professionals engaged in nuclear forensics in agriculture. Embedding competency-based principles into training design ensures instructional relevance, promotes autonomous learning, and fosters sustained professional development—particularly crucial in technical fields where scientific rigor, traceability, and ethical accountability are paramount. As illustrated in the framework, the training course titled Advancing Variety Differentiation and Geographic Origin Provenance is anchored on a cyclical process of design, implementation, and evaluation, underpinned by foundational adult learning theories and aligned with the principles of continuing professional development.

At the core of this model lies a pedagogy grounded in science education constructs such as learning task design, scientific literacy, science identity, multimodal learning, and a functional view of language. These elements collectively inform the design of instructional activities that are contextually embedded and learner-responsive. The integration of adult learning theories supports the tailoring of content to professional learners' prior knowledge and experience, while evaluation feedback loops ensure the adaptability and responsiveness of the training materials to emergent learning needs. This dynamic interplay ensures that the modules not only develop technical competencies in isotope and elemental analysis but also cultivate reflective, adaptive, and literate practitioners—key to strengthening institutional capacities in food authenticity and agricultural forensics.

Figure 1

The Conceptual framework for the Development and Evaluation of the Training Module



Methodology

This study employed a mixed developmental research approach, integrating Type I and Type II models as defined by Richey and Klein (2005). Type I focused on the systematic design and development of a training module in nuclear forensic applications for agricultural traceability, while Type II addressed the iterative validation and refinement of both instructional content and delivery mechanisms under real-world implementation conditions. This methodological alignment facilitated the rigorous integration of scientific competencies, pedagogical principles, and domain-specific training needs.

Training Module Development and Target Participants

The training module was developed for science professionals engaged in nuclear forensics, specifically within the domain of agricultural provenance and varietal authentication. Target participants included nuclear scientists, isotope analysts, soil and agricultural chemists, geochemists, and data scientists working in analytical laboratories or regulatory agencies. The curriculum was designed to integrate technical depth with applied relevance, supporting capacity building in elemental profiling, stable isotope analysis, and AI-assisted classification systems for varietal differentiation.

Instructional Design Framework

The design phase adopted the SMART framework (Specific, Measurable, Achievable, Relevant, Time-bound) to structure learning outcomes, ensuring alignment with technical and professional benchmarks. Training content was scaffolded across three interdependent knowledge domains: (a) content knowledge situating nuclear forensics in agricultural science; (b) procedural knowledge covering experimental design, instrumental calibration, and data analysis; and (c) epistemic knowledge addressing the nature, limitations, and iterative processes of scientific inquiry (OECD, 2023).

Pedagogical Foundations

The instructional strategy was grounded in Mezirow's Transformational Learning Theory and Kolb's Experiential Learning Cycle. Mezirow's model emphasized critical reflection, encouraging professionals to interrogate their assumptions and adapt to paradigm shifts in nuclear forensic methodologies (Fleming, 2018). Kolb's experiential cycle (1984) guided the sequencing of learning experiences—from concrete tasks (e.g., isotope data interpretation) to reflective observation, abstract conceptualization, and active experimentation. This cyclical process ensured that learners acquired, internalized, and operationalized new scientific competencies.

Visual and Language Integration

To optimize cognitive processing, the module's visual design was informed by Sweller's Cognitive Load Theory (2011). Diagrams were categorized based on Tang's (2023) typology—narrative, analytical, classificational, and metaphorical—to facilitate comprehension of complex analytical workflows and conceptual models in isotope geochemistry and machine learning. Linguistically, Fang's (2005) functional view of scientific language was employed to support register transitions, enabling accessibility without sacrificing terminological precision.

Assessment Framework

Assessment methods were designed to emphasize skill application and longitudinal competency development. Performance-based assessments required participants to apply scientific reasoning and analytical methods to solve domain-specific problems. Complementing this, portfolio-based assessments captured the progressive refinement of competencies over the course of the module, following the documentation principles outlined by Gyamfi et al. (2023).

Science Identity and Motivation

A critical component of the training involved reinforcing participants' science identity—defined by the PISA 2022 Science Framework as the capacity to perceive oneself as a scientifically literate professional with agency and social relevance. Drawing on Salvadó et al. (2021), the module addressed systemic barriers to scientific identity formation and incorporated strategies to strengthen learners' confidence, inclusion, and professional visibility in science-based fields.

Qualitative Validation and Thematic Analysis

To triangulate the quantitative evaluation results, semi-structured interviews were conducted with content and pedagogical experts. Data were analyzed using Braun and Clarke's (2006) six-phase framework for thematic analysis. Transcripts were coded at the sentence level, enabling a granular interpretation of expert insights. Cohen's kappa was computed to assess intercoder reliability, with $\kappa \geq 0.80$ considered acceptable. Discrepancies in coding were resolved through peer discussion, ensuring consistency and thematic validity.

Results and Discussion

Training Objectives

All five indicators under the Training Objectives dimension received a median score of 4, interpreted as Strongly Agree. This result affirms the clarity, specificity, and interdisciplinary scope of the training's goals. Expert validators underscored that the objectives effectively scaffolded both conceptual understanding and practical skills in nuclear forensics, isotope analysis, and machine learning—a design approach consistent with the SMART framework (Doran, 1981).

Training Content

Content evaluation also yielded a unanimous *Strongly Agree* rating across eight items. Validators highlighted the scientific accuracy, currency, and integrative nature of the modules. Content was commended for its alignment with real-world forensic practices and its capacity to foster advanced analytical reasoning. This resonates with the instructional principle of constructive alignment (Biggs, 2013), where learning outcomes, instructional activities, and assessments converge to support deep learning.

Pedagogical Approaches

The pedagogical strategies adopted were positively affirmed with *Strongly Agree* medians for all six items. The integration of Mezirow's (1991) Transformative Learning Theory and Kolb's (1984) Experiential Learning Cycle supported participant engagement, critical reflection, and iterative skill application. Validators noted that these approaches stimulated analytical thinking and peer discourse, echoing principles of adult learning theory (Knowles, 1984; Pappas, 2023).

Visual Aids and Illustrations

Visual design elements received high approval, particularly in facilitating the understanding of complex scientific and AI-driven concepts. All five indicators received a median of 4 (*Strongly Agree*), with feedback emphasizing effective use of callouts, consistency, and instructional clarity. This aligns with dual coding theory (Clark & Paivio, 1991) and Sweller's (2011) Cognitive Load Theory, which collectively emphasize optimizing cognitive processing through multimodal representation.

Language Use

Three indicators under language use all received a median of 4, reflecting successful navigation between technical specificity and conceptual accessibility. Validators recommended the inclusion of glossaries and additional formatting cues to further reduce barriers to comprehension—an approach consistent with Universal Design for Learning principles (CAST, 2018) and Fang's (2005) functional linguistic framework.

Assessment Strategies

Assessment strategies were also highly rated (*Strongly Agree*), particularly for their emphasis on portfolio-based and performance-based assessments. These techniques enabled longitudinal tracking of participant growth, competency development, and real-world application, consistent with Wiggins & McTighe's (2005) framework for authentic assessment and Sadler's (1989) emphasis on formative feedback.

Science Identity Formation

The training module was lauded for fostering science identity—a critical dimension in professional development—across all four indicators. Expert feedback emphasized that the module not only enhanced scientific self-efficacy but also reconnected participants to their roles within broader scientific and societal ecosystems. This finding aligns with Carlone and Johnson's (2007) identity framework and the affective dimension of the PISA Science Framework (OECD, 2018).

Expert Validator Perspectives on Module Design and Effectiveness

Interviews with expert validators revealed five core strengths of the training module, affirming its pedagogical soundness and professional relevance. First, the module was commended for its instructional design and learner engagement, grounded in experiential and transformative learning. Validators emphasized the value of hands-on, reflective activities that promoted applied thinking. As one expert expressed, *"Na-challenge na mag-isip and i-apply yung nabasa,"* pointing to the module's success in fostering critical synthesis and practical application—key attributes of Mezirow's and Kolb's adult learning frameworks. Second, validators praised the module's coherence and alignment, citing its clear structure and logical progression. *"The instructional design clearly defines its learning objectives and provides a specific focus on each content of the training module,"* remarked another evaluator, underscoring the successful integration of SMART objectives and constructive alignment. However, feedback also flagged minor concerns over dense information delivery, reinforcing the need to incorporate cognitive load management strategies such as content chunking and improved whitespace.

Third, the module's visual aids were acknowledged as effective tools for simplifying complex forensic concepts. Experts highlighted that *"illustrations and diagrams clarified abstract concepts,"* aligning with dual coding theory. At the same time, they recommended standardizing figure labels and avoiding visual clutter to further enhance learning efficiency. Fourth, the module's language register effectively balanced technical precision with accessibility.

Validators appreciated the clarity of presentation, though suggested the addition of glossaries and formatting cues to scaffold understanding. These recommendations support inclusive communication strategies informed by Fang's (2005) functional linguistic view and Universal Design for Learning. Finally, the module was recognized for its impact on science identity and professional integration. One expert shared, *"Bumabalik yung passion,"* signaling the training's ability to rekindle professional purpose and reinforce participants' place in the scientific community. This aligns with Carlone and Johnson's (2007) framework, highlighting recognition, competence, and performance as essential to sustained STEM engagement

Summary

This study addressed a critical gap in Philippine agricultural science by developing and evaluating a training module aimed at capacitating professionals in the geographic and varietal differentiation of *Dioscorea alata* L. "Kinampay" using nuclear forensics methods. The training program integrated advanced analytical tools—including XRF elemental profiling and stable isotope analysis—within a pedagogically grounded, competency-based framework to support sustainable food authenticity systems. Anchored in the principles of adult learning, science identity formation, and continuing professional development (Frank et al., 2010; Moineau et al., 2010; Salvadó et al., 2021), the module was evaluated through mixed-methods research combining Likert-based expert validation and qualitative thematic analysis.

The results of the module evaluation demonstrated uniformly high levels of expert agreement across all seven instructional dimensions: objectives, content, pedagogy, visuals, language, assessment, and science identity formation. Validators affirmed the module's capacity to deliver conceptual depth, methodological precision, and interdisciplinary integration, citing its alignment with contemporary educational theories such as Mezirow's Transformative Learning, Kolb's Experiential Learning, and Sweller's Cognitive Load Theory.

Feedback also emphasized that the module's design fostered both analytical competence and motivational engagement, as reflected in remarks such as *"Na-challenge na mag-isip and i-apply yung nabasa" and "Bumabalik yung passion."* These qualitative insights underscore the module's ability to advance both technical proficiency and professional identity among science practitioners in agriculture.

While overall reception was positive, expert commentary highlighted specific areas for refinement. These included enhancing cognitive ergonomics through better content chunking, improving visual clarity through standardized diagram labeling, and supporting inclusive comprehension through glossaries and formatting scaffolds. These suggestions align with established instructional design frameworks and underscore the importance of iterative development in maintaining instructional quality and accessibility.

Conclusion

The study concludes that the developed training module offers a pedagogically robust and scientifically rigorous tool for advancing capacity in nuclear forensic applications for agricultural traceability. Its design reflects an effective convergence of scientific literacy, technical skill-building, and learner-centered pedagogy. Moreover, it exemplifies how competency-based continuing professional development models can be adapted to emerging domains such as agri-food forensics, where scientific accuracy, traceability, and policy relevance intersect.

Recommendations

To ensure the long-term effectiveness and institutional relevance of the training module, it is recommended that future iterations integrate a more robust learner-centered design informed by cognitive and pedagogical feedback. Specifically, enhancements should address the management of cognitive load through improved visual hierarchy, modular content chunking, and the incorporation of scaffolded glossaries for specialized terms. These refinements will optimize knowledge retention and accessibility, particularly for interdisciplinary learners entering the field of nuclear forensics in agriculture. Embedding these improvements within the instructional workflow will strengthen the alignment between technical content and adult learning theory, resulting in a more coherent and user-responsive training experience.

Additionally, the development of a multimodal and hybrid delivery framework is essential to extend the module's reach and adaptability. This entails integrating digital simulations, interactive data environments, and asynchronous learning pathways that support both remote and in-person participation. Leveraging these technological enhancements not only expands access for professionals in geographically dispersed or resource-limited settings but also reinforces the application of isotope and elemental analysis techniques in authentic scenarios. By embedding these tools into the module's structure, the training program can better serve its role in building a competent and agile workforce capable of supporting agricultural traceability and food authenticity efforts at the national and institutional level.

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