Research Article

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Cultural Roots, Scientific Fruits: Exploring the PAPEDA Framework in Ethno-STEM Teaching

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Abstract

This article, with an emphasis on conceptual discussion, explores the possibilities of ethno-STEM teaching through the innovative framework of PAPEDA, offering a practical approach to blending indigenous knowledge with STEM disciplines. The PAPEDA framework—Provide, Analyze, Perform, Evaluate, Disseminate, Assessment—depicts a structured but flexible approach to dealing with the very real issues of ethno-STEM implementation, while facilitating the benefits of the integration of technoscience. Through comparison with established cognitive models such as 5E and 7E, the authors will illustrate the unique strengths of PAPEDA in the creation of a culturally responsive worksheet for STEM teaching that is engaging for students. The article will show how the PAPEDA framework is not only enriching in terms of cultural relevance, but also successful in integrating the principles of ethnoscience and STEM-based human technology, promoting critical thinking and problem-solving skills, fostering scientific literacy within cultural contexts, and discussing options for its implementation in various learning settings. This article will also discuss the role of the Engineering Design Process as an integral aspect of the implementation strategies for PAPEDA. It will also discuss the potential of future research areas including longitudinal studies, international adaptations, and assessment tools. The conclusion of the article will make claims that the PAPEDA framework for ethno-STEM implementation is a fruitful opportunity to revolutionize science education to provide an inclusive, relevant, and efficient STEM education that can transform science curricula to better serve diverse students and address the Global Grand Challenges while being culturally-based.

Keywords: *PAPEDA framework, Ethno-STEM, diversity in STEM, cultural competence, inclusive education*

1. Introduction

The contemporary clash between classical cultural knowledge and novel Science, Technology, Engineering, and Mathematics (STEM) approach is indeed an impending dilemma that seems "cannot be fixed". Many students of indigenous backgrounds and diverse cultural settings seem unable to bring that cultural heritage to contemporary science education, thereby becoming less engaged in STEM fields and, consequently, drawing lower achievement levels (McClain & Colina Neri, 2022; Owens & Ramsay-Jordan, 2021; Yerrick & Ridgeway, 2017). This disconnect impacts the outcomes of education and remains an instigator of losing the valuable traditional knowledge that could play a complementary role in addressing modern technological challenges (Augustin-Behravesh, 2023; Bruijnzeel et al., 2022).

Recently, a new promising trend referred to as Ethno-STEM has appeared as a potential solution to the traditional problem. The integration of ethnoscience with STEM approaches - otherwise known as ethno-STEM - is quickly emerging as a promising way to more inclusively, meaningfully, and engagingly teach science to all students (Nugraheni et al., 2023; Sari et al., 2023). Ethno-STEM, mentioned firstly by Sudarmin, seeks to bridge the gap between traditional cultural knowledge and modern scientific understandings by recognizing that scientific inquiry, as well as the development of new technologies, can be rooted in a variety of cultural contexts (Sudarmin, 2014; Sumarni, 2018). This integration helps students not only gain a greater appreciation for their cultural roots (Sudarmin et al., 2023), but also increase their understanding of science by connecting science concepts to familiar cultural practices and social beliefs (Primadianningsih et al., 2023).

Despite the perceived benefits of ethno-STEM, there is little research that has demonstrated effective model-based strategies for integrating cultural knowledge into existing ethno-STEM approaches (Yuecheng, 2023). Deploying and integrating ethno-STEM in classrooms has been challenging, particularly because teachers and researchers do not have clear, straightforward frameworks for forced insertion of cultural knowledge into mainstream STEM curriculums (Aslam et al., 2023). What is needed is a practical, accessible framework that can structurally and thematically engage students in doing ethno-STEM. Considering these concerns, PAPEDA provides a promising avenue for integrating ethno-STEM in the classrooms. PAPEDA -- representing Provide, Analyze, Perform, Evaluate the results, Disseminate the results, Assessment -- provides a structured and flexible way to integrate ethno-STEM in practice.

The framework encourages a systematic but flexible approach to integrating indigenous knowledge with STEM disciplines and provides culturally responsible educational experiences incorporating traditional wisdom with scientific thought. Developed based on previously established models such as the 5E and 7E Models, PAPEDA offers a holistic approach to tackling the essence of conveying a culturally responsive STEM approach while maximizing the benefits of technology integration.

The article investigates the evolution and theoretical underpinning of the PAPEDA framework and how it has adopted its role in evolving with modern educational demands yet not losing valuable cultural capital. PAPEDA develops the conceptual theory that traverses its early use and operation and shows in this way how it transcends both the cultural and educational aspects of modern education. The focus on introducing the Engineering Design Process is anticipated to equip the students to grapple with contemporary challenges while being sensitive to the current situation and culture.

This article shows the origins and developments of PAPEDA framework while providing insights for educators on how to craft given cultural wisdom with a modern STEM approach into learning experiences that are academically exhaustive yet culturally enriching. This understanding is fundamentally needed as education systems worldwide are aspiring to become more inclusive and effective in preparing diverse student populations for future challenges.

2. Understanding Ethno-STEM

The presence of underrepresented groups in STEM fields is a significant issue (Jehangir et al., 2023; Owens & Ramsay-Jordan, 2021). However, not all people recognize this problem exists (Tsui, 2007; Whitcomb & Singh, 2021). Recent statistics paint a sobering picture of underrepresentation, particularly among racial/ethnic minority groups (O'Brien et al., 2015), women (Wong & Copsey-

Blake, 2023), and individuals from low-income backgrounds (Krishnan et al., 2023). These underrepresented groups are even more likely to be missing within certain STEM disciplines (Whitcomb & Singh, 2021), higher levels of academia (von Vacano et al., 2022), and leadership roles in the industry (Martínez et al., 2023; Shaikh et al., 2019).

Addressing the diversity gap in STEM fields is not only important for equity (Goldberg et al., 2023; Ramiah et al., 2022), but it is also vital for the advancement of these fields. Research by BrckaLorenz et al. (2021), Erbaş (2013) and Purwanto et al.(2020) has shown that diverse teams are more likely to develop innovative solutions and promote scientific advances. As the problems we face on a global scale become increasingly complex, the need for a diverse STEM workforce, with individuals who bring unique perspectives and ways of thinking to problem solving, is critical (Lee & Amir, 2022; Salzman & Douglas, 2023).

The potential of ethno-STEM is vast and multifaceted, creating transformative opportunities for education and scientific advancement alike. The central value of ethno-STEM lies in its conception as a powerful cultural bridge in the STEM field (Asmaningrum et al., 2021), and through this process serves to render STEM fields more accessible and relevant to students from a diverse range of backgrounds (O'Brien et al., 2015). It incorporates cultural contexts and traditional knowledge into STEM theory (Sumarni, 2018), thereby setting up a situation where students are injected with the ability to see their experiences and heritage in their education, allowing a more inclusive learning environment. This in turn increases in ability to engage with STEM approach and a love of the subject, while also serving to boost the confidence of the learner by acknowledging those who might feel distanced from the traditional STEM narrative (Berisha & Vula, 2021; Ma'rufi et al., 2021).

Ethno-STEM refers to a novel approach to education that aims to combine the knowledge, practices, and perspectives of a culture with traditionally Western STEM curricula (Estepp et al., 2023; Woolworth & Thirumurthy, 2012). At its core, Ethno-STEM recognizes that scientific and technological understanding is not limited to Western paradigms, and exists in diverse cultural contexts worldwide (Gumilar et al., 2022; Primadianningsih et al., 2023). The idea of Ethno-STEM hopes to make STEM education more inclusive, relevant, and engaging for people from various cultural backgrounds by acknowledging and incorporating their heritage and experiences as part of the learning process (Chahine, 2021; Sudarmin et al., 2023).

Ideally, Ethno-STEM is teaching a system of knowledge that would be culturally responsive and adaptable teaching methods -i.e., culturally responsive pedagogy (Ferri & White, 2024; Rahmawati & Ridwan, 2017). Teachers should be capable of acknowledging that they affect change when people learn (Bourn, 2016; Buechel, 2022): by doing so, they affect change in learners. By promoting representation, Ethno-STEM further strives to elevate diverse perspectives and contributions from a range of individuals within STEM and beyond. An integrated pattern for the Ethno-STEM approach was designed (Sudarmin et al., 2022) as in Figure 1.

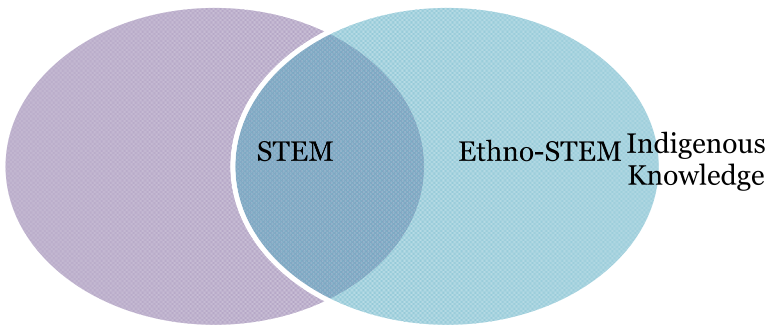

Figure 1. Ethno-STEM approach

Furthermore, ethno-STEM unlocks the potential to greatly enhance STEM fields by enabling the opportunity to be innovative with the integration of diverse knowledge systems. For example, the research by Sudarmin et al. (2023) revealed that traditional ecological knowledge has the potential to provide radical new perspectives for sustainable practices and the conservation of the environment; and research by Laurents (2014) shows that indigenous mathematical constructs could allow for novel problem-solving perspectives for computer science and engineering. This cross-pollination of ideas can lead to breakthroughs and unconventional solutions for complex global challenges.

Moreover, the emphasis on cultural diversity in ethno-STEM's treatment of the process of scientific investigation allows for a more holistic (McCann & Marek, 2016) and thoughtful understanding of the world (Dare et al., 2021). By incorporating and validating diverse ways of knowing, ethno-STEM further serves as a vital force in renewing and safeguarding traditional knowledge which has the potential to be lost. For example, research by Rizki et al. (2022) that explore the potential of traditional engklek (hopscotch) games as media of physics concepts in the ethno-STEM approach. Or research by Tresnawati et al. (2020) that used traditional batik from Ciwaringin as project for science learning using the ethno-STEM approach. It serves not only to promote cultural conservation (Sudarmin et al., 2023) but also as a way for valuable insights formed and passed down to contribute to and enrich our collective scientific understanding (Martawijaya et al., 2023; Marufi et al., 2021; Primadianningsih et al., 2023). The potential of ethno-STEM is not only for the classroom, but also to create a more inclusive, innovative, and culturally responsive scientific community that can solve the complex global and interconnected challenges faced by society.

3. The PAPEDA Framework: A Practical Model to Ethno-STEM

The PAPEDA framework is a structured approach that is pragmatic for implementing ethno-STEM in educational environments; it offers a step-by-step method for blending cultural information with STEM subject matter that can address the problems that observers have with implementing ethno-STEM. PAPEDA stands for the six phases - Provide, Analyze, Perform, Evaluate, Disseminate, and Assessment, which encompasses a full learning cycle that encourages both cultural and scientific inquiry.

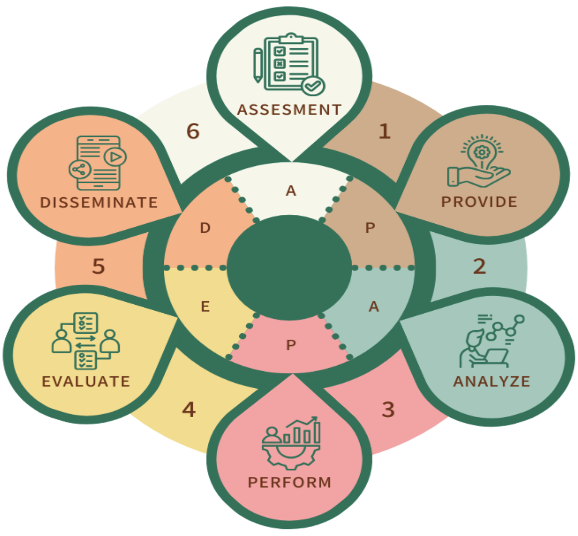

Figure 2. PAPEDA Framework

The PAPEDA syntax framework starts with "**Provide**", in which teachers present a problem or case study situated within a cultural context. This is an important first step, as teachers set the stage for ethnoscience activities that will allow students to access familiar cultural practices or phenomena. There is potential for students to really connect with what they know how to do culturally and therefore can connect to a more familiar world. For example, the use of customary law to address environmental pollution (Asmaningrum, et al., 2022), the use of natural dyes in making batik (Sudarmin et al., 2020), and the use of local knowledge in the field of medicine (Sumarni et al., 2022). Giving students a culturally important problem or case study will let students know that the STEM in their lives and communities is important (Ferri & White, 2024).

Following this, the next stage "**Analyze**" is about inviting students to widen their investigation in the form of exploring the issue through various research methods. The students could conduct literature reviews or may deliberate with community members or cultural experts. This part of the model seamlessly infuses STEM practices when the students apply scientific practices to analyze (Asmaningrum et al., 2021), perhaps design prototypes or models to work toward addressing the problem that was identified in the previous stages. Similar to all previous stages of the model, this stage works to cultivate critical thinking and problem-solving skills, and most significantly develops the capacity to bring together traditional knowledge with contemporary scientific norms (Irwanto et al., 2024; Yazidi & Rijal, 2024).

Using the Engineering Design Process (EDP) within the Analyze stage of the PAPEDA framework presents a unique opportunity, particularly when challenging students to develop prototypes that address culturally relevant issues. The integration of EDP into the Analyze stage both enhances the STEM component of ethno-STEM and maintains cultural relevancy. As students work to analyze the issue through literature reviews and community interviews, they can begin EDP by defining the problem in engineering terms (Manuel et al., 2023).

This integration will allow students to apply science and mathematics to real-world, culturally significant problems (Widiastuti et al., 2022). As students brainstorm solutions, they can draw upon their cultural knowledge and modern engineering principles to ensure that innovative solutions are culturally responsive. The iterative nature of EDP is conducive to the PAPEDA framework as students research, design, test, and redesign their prototypes. This is a phase where students can draw initial sketches, design 3D models, or create small physical prototypes all of which are informed by the cultural context outlined in the Provide stage of PAPEDA.

Using local materials or traditional techniques with modern engineering tools not only bridges traditional ways of knowing and contemporary STEM applications but also provides the perfect opportunity for cultural relevance. By integrating EDP into the Analyze stage, students are expected to not only develop problem-solving skills, and critical thinking but also demonstrate how engineering can be applied to both preserve and innovate within cultural frameworks (Estapa & Tank, 2017). This approach also has the potential of developing solutions that are culturally appropriate sustainable and resonant with the local community in addition to developing a deep understanding of core STEM concepts for students (Widiastuti et al., 2022). It is also meant to provide a convenient pathway into the Perform stage where students can present not only findings but also tangible culturally informed engineering solutions (Abd-Elwahed & Al-Bahi, 2021).

The "**Perform**" stage is about creating space for students to share their work and findings. Again, students will have the opportunity to share their presentations in the form of a formal presentation, a poster presentation, or a creative presentation such as a vlog (Asmaningrum et al., 2021). This phase is about students "performing" their knowledge. Most importantly, this phase supports communication (Han et al., 2021) and peer learning when students share (Starr et al., 2022) their culturally informed STEM solutions with a larger audience, their classmates.

Baselga et al. (2022) support this claim, presenting new findings from a study evaluating an innovative, student-centered, performance-based drama pedagogy for STEM at the secondary school level. The drama was evaluated, English and Spanish case studies, with a total of 2089 students. The drama is an effective method of facilitating a 'dialogue' between students and researchers, promoting students' reflection about scientists as role models, gender inequalities in STEM, and ethical issues in STEM careers and science research. The drama has also increased young people's positive attitudes towards, and interest in, science, scientists, and science jobs and dispelled some of the commonly held stereotypes about science. This indicates that the drama used in this study supported young people's aspirations, and did not prevent them from critically engaging with the benefits and drawbacks of scientific progress for themselves.

The stage of "**Evaluate**" is about assessment in the form of teacher formative assessment. In this phase, the teacher will provide feedback on the process and prototypes. This feedback is important for developing the student's understanding and to make anything that needs to change (Kanna. M.R et al., 2024; Vu & Viet Nga, 2023), i.e. process, prototype, so, that for the next iteration, the prototypes and process have been refined and are purposeful (Molina-Moreira et al., 2023).

In the "**Disseminate**" stage, the students have the opportunity to share their final product after they have received feedback about changes that may need to occur. This stage may include the presentation to a larger audience such as community members, and could be a representation of the real-world impact of their ethno-STEM project and could positively strengthen the relationship between cultural knowledge and scientific progress.

The phase of dissemination is very significant in science learning, as it bridges the gap to apply and use scientific knowledge, enhancing understanding and interest in scientific information among students (Beck et al., 2019). The dissemination phase involves the delivery and communication of scientific findings and educational materials to improve the understanding and motivation of the students (Zuanetti, 2021).

The final stage, "**Assessment**", serves as a summative evaluation of students' science content comprehension as well as their development of skills related to scientific literacy, problem-solving, and cultural competency. Through the comprehensive nature of the assessment, teachers can gauge the adequacy of STEM learning objectives and cultural understanding and the need to adjust objectives or instruction where required (Stăncescu, 2017).

The assessment stage in science education becomes a crucial part of the process for valid reasons that are considered to be part of the larger framework of science learning (Harrison, 2015). Furthermore, evaluation in science and science education is not just an endpoint, it's an integral piece of the learning process to help improve - it is feedback, and therefore, evaluation and feedback are required to move teaching forward so that outcomes are improved (Moeed, 2015). Providing a science learning environment that encourages and builds scientific reasoning (a long-term outcome of inquiry-based learning) and higher-order thinking as demonstrated by the use of valid and reliable test items - all are critical for scientific literacy, and STEM approaches. Therefore, evaluation in science learning is a must – not only to measure and assess student learning but to summarize and improve the educational process that should allow for student development of critical thinking, metacognition, as well as scientific literacy (Rustaman, 2017).

The PAPEDA syntax's framework enables teachers to address many of the challenges that face the development and implementation of ethno-STEM. The PAPEDA framework provides teachers with a clear path through some of the complexities of integrating cultural knowledge into the curriculum and STEM content. The community involvement and real-world applications inherent in the PAPEDA cycle make a strong case for a more relevant STEM education. The iterative nature of PAPEDA, with an intentional focus on analysis, performance, and dissemination, contributes to deep learning and skill development.

What stands out in PAPEDA that is different from more established instructional models like 5E or 7E is the incorporation of cultural domains and the emphasis on dissemination and community engagement. It includes a few of the things that other models emphasize, such as inquiry-based learning and assessment, but PAPEDA's structure makes it unique and particularly suitable for ethno-STEM implementation. PAPEDA is significant because it provides a practical and comprehensive structure that educators can use to create a culturally rich and scientifically rigorous STEM educational opportunity that could revolutionize STEM education for diverse student populations.

4. Comparative Analysis: PAPEDA, 5E, and 7E Models

It is useful to contrast the PAPEDA framework to ethno-STEM approaches with other more established instructional models, like the 5E and 7E models, to understand the unique contributions of PAPEDA to ethno-STEM education. These models are commonly used in science education and while they have some similarities to PAPEDA, they lack the specific advantages for implementing ethno-STEM enhanced by PAPEDA.

The 5E model (Engage, Explore, Explain, Elaborate, Evaluate) and its expansion, the 7E model (adding Elicit and Extend), are inquiry-based models in science education designed to promote more active learning in science education, which includes sharing in the construction of knowledge, student-centered learning, and hands-on experiences. While these models can serve as good structures for science instructional planning they do not address the integration of cultural knowledge, which is a main feature of ethno-STEM.

In some respects, PAPEDA is similar to these instructional models, especially in that it is based on inquiry learning and focuses on assessment. The Provide of PAPEDA could be analogous to the 5E/7E Engage phase, and the point of Provide is to spark students' interest in the learning and attend to their prior knowledge. The Analyze of PAPEDA is more like the Explore and Explain of the 5E/7E and the students are engaging in analyzing and informing about the learning. The Evaluate of PAPEDA has similar qualities in all models. It is where students and teachers are working through how assessment can inform learning and teaching.

PAPEDA, however, clearly stands out in contrast to other models in various respects. One distinguishing feature is that PAPEDA specifically includes the cultural context upfront, which makes it very well-suited to ethno-STEM implementation. The "Provide" stage of PAPEDA was made to deliver culturally relevant problems or cases so that the learning process is shaped by and extended from the cultural experiences of the student. This is unlike the 5E and 7E models, which are flexible, but do not inherently prioritize cultural relevance.

There are also specific stages in PAPEDA that are dedicated to performance and dissemination ("Perform" and "Disseminate") that are not expressly present in 5E/7E models. These stages ask students to make sense of and share their learning in multiple formats including potentially sharing with a community audience. This part of PAPEDA provides a bridge between classroom learning and application to relevant world contexts, a significant aspect of ethno-STEM education.

The "Analyze" stage in PAPEDA is more intricate than the "Explore" stage of 5E/7E, particularly in that the stage calls for literature reviews, interviews, and prototype creation. This approach allows for a more substantive fusion of cultural knowledge with scientific inquiry and engineering practices.

Finally, the "Assessment" stage of PAPEDA goes beyond the "Evaluate" stage of 5E/7E by specifically measuring not only mastery of a scientific concept, but instead also measuring science literacy, problem-solving, and potentially cultural competence. The broader measurement strategies in PAPEDA align more with the goals of ethno-STEM education.

The 5E and 7E models are useful models of science education, but PAPEDA is structured to more directly meet the goals of ethno-STEM. PAPEDA provides a structure that seamlessly incorporates culturally-based knowledge and practices with STEM concepts, welcomes community engagement, and encourages application in a real-world, culturally-based context. PAPEDA provides an effective model for educators desiring to implement ethno-STEM in their classrooms, and students in diverse classrooms benefit from the model as it serves as a bridge connecting traditional cultural knowledge to scientific understanding.

5. Potential Benefits of PAPEDA in Ethno-STEM Teaching

The implementation of the PAPEDA framework in the ethno-STEM approach would present a valuable opportunity with the potential to transform the learning experiences and outcomes for students from multiple cultural backgrounds. One of the major benefits is the increased cultural relevance and student engagement that the ethno-STEM approach would offer. Beginning STEM conversations in culturally familiar spaces through PAPEDA is one way to make science and technology more accessible and relevant to those who would otherwise feel disassociated from traditional STEM curricula. This cultural relevance could in turn support intrinsic motivation when students begin to see the connections between their cultural background, everyday life, and the scientific concepts they must learn(Nelson-Barber, 2023; Yuecheng, 2023). This in turn could lead to heightened engagement, curiosity, and motivation in the STEM fields as a way to potentially mitigate the effects of underrepresentation in STEM fields by making STEM disciplines more inclusive and relevant for an assortment of students.

The PAPEDA framework in particular offers to enhance the integration of STEM concepts and ethnoscience as well. PAPEDA does not treat the integration of cultural knowledge with STEM knowledge as an afterthought or as superficial. Instead, PAPEDA offers a framework that is about the integration of cultural knowledge and modern scientific understanding in a structured way. The model encourages students to value and consider how traditional wisdom and contemporary theory or practice can inform one another.

For example, during "Analyze," students are asked to review academic and non-academic literature and conduct interviews, to provide a space where students can bridge academic research with community knowledge. This process not only helps to deepen students' understanding of STEM concepts but also provides opportunities for students to validate and maintain cultural knowledge, which in turn provides a holistic and inclusive manner to think and context about science and technology.

Additionally, the PAPEDA framework is a developmentally appropriate model for fostering critical thinking and problem-solving skills. The PAPEDA framework focuses on analyzing culturally relevant, authentic problems and designing solutions that stimulate students' creativity and critical thinking. As students traverse crossing traditional practices with scientific practices in the modern world, they learn to see problems from different perspectives, supporting them to be cognitively flexible and innovative thinkers (Ariyatun, 2021; Hebebci & Usta, 2022; Hiqmah et al., 2023). The iterative elements of the model, as seen explicitly in the "Analyze" and "Evaluate" stages, create a model that mirrors the science and engineering practices students will see as they move through education and into STEM professions or other areas where complex problem-solving skills are needed.

Another significant benefit of the PAPEDA framework is the promotion of scientific literacy within cultural contexts. As students work through the entire scientific inquiry process—who identifies, makes solutions, and shares within a culturally relevant context, they can come to a more profound understanding of what science is. Students will not only know about science, but also how science works, how it happens in the world, and how it is evaluated and applied in the world beyond school(Wibowo et al., 2023; Zeegers et al., 2023). It could help take down science from a facts view of science to something more dynamic and culturally related as inquiry and uncovering.

Dissemination gives a unique benefit to the PAPEDA framework, as students will be invited to share findings and solutions with a broader audience, which could include community members. This unique element can help connect schools to their communities, which could validate cultural knowledge in academic settings and could also bring in community-based knowledge for real, meaningful innovations. It additionally offers students valuable experience in science communication, a capability that is increasingly necessary in our globally interconnected future (Widiastuti et al., 2022).

The full assessment approach in PAPEDA, which measures not just understanding of scientific concepts, but also broader skills such as problem-solving, and potentially cultural competence, aligns with modern educational goals of creating culturally literate, well-rounded individuals. It is possible that with a broader assessment, we can better understand student growth and preparedness for the demands of future academic and professional opportunities in a multicultural and global society.

Overall, the inclusive potential explanations of PAPEDA framework in ethno-STEM approaches are substantial, as they address many of the challenges in traditional STEM approaches and provide new approaches to culturally responsible, approachable, and effective empirical exploration. PAPEDA framework can make a substantial difference in STEM approaches by combining culturally relevant knowledge with inquiry in science to create a STEM subject that is more relevant, more meaningful, and more usefully impactful for everyone.

6. Practical Implementation of PAPEDA Model in Ethno-STEM Classrooms

A thoughtful approach is essential for incorporating the PAPEDA framework into ethno-STEM classrooms to maximize their success. Teachers eager to utilize the PAPEDA framework will find guidance and instruction on how to integrate it effectively. In the first stage, teachers should invest time in learning about their students' backgrounds and the community in which they are teaching. This work may involve research, community contacts, and working with cultural experts or elders. Data collection in this phase will help teachers facilitate learning by putting into place the proper cultural contexts in both their lessons and the authentic "Provide" stage for the students that connect with their experiences. One possible action might be to establish a cultural inventory of local practices, beliefs, and challenges that link up with STEM content and could serve as a resource for creating relevant problems.

In the classroom, PAPEDA can be put into practice in a variety of ways for different subject areas and grade levels. For example, in a middle school science class where students are studying ecosystems, the teacher may introduce a real local environmental issue that impacts the community in the "Provide" stage. For example, water pollution in a river near a community with a cultural tie to it. Here, students will move into the "Analyze" stage, where they may research water quality literature and interview community members on traditional water purification methods. This "Analyze" stage could include water testing in the field or experiments, and group conversations to come up with potential solutions. The solution might be a blend of traditional and modern knowledge.

In the 'Perform' stage, students could produce multimedia presentations or build small models of their project ideas, and in the 'Evaluate' stage, students could review their work using peer reviews and teacher feedback aimed at assessing the accuracy of the science and cultural sensitivity. In the 'Disseminate' stage, students could plan a community event to share their findings and prototypes, inviting local experts and stakeholders to attend and provide feedback. In the 'Assessment' stage, students would be evaluated not only on their understanding of ecosystem content but also on how they integrated cultural knowledge and addressed a problem-solving process.

Teachers could plan for this implementation by creating a bank of ethno-STEM lessons and resources aligned with the PAPEDA framework. This might include templates for each of the phases of the process, a collection of case studies that illustrate cultural relevance, and rubrics that assess STEM content knowledge and cultural competence. Additionally, designing this bank of resources in collaboration with other teachers in one's high school or across disciplines might be another way to enrich this resource bank and facilitate interdisciplinary ethno-STEM projects.

Technology can be very useful in supporting the implementation of PAPEDA. For example, digital platforms can be used to connect students with cultural experts who are not available in the local region, virtual field trips could provide access to additional cultural experiences, and data visualization software could aid students as they analyze and present their findings in engaging formats. In addition, web-based collaboration platforms can support the 'Disseminate' stage and allow a broader audience to consider, review, and even provide feedback on the work, and students might even collaborate on projects in a culturally meaningful way with students in a different cultural context.

However, teachers need to anticipate potential challenges in enacting PAPEDA. One common challenge is the scheduling constraints of school. To combat this, teachers could potentially adopt extended project-based learning units that span several weeks, to afford students the time to meaningfully engage with each phase of the PAPEDA process. Another challenge might be the absence of easily accessible culturally relevant STEM resources. They might encourage students to invent these resources, leveraging them as a solution to the absence of resources and as an opportunity to encourage students to engage in the co-creation of knowledge.

Additionally, teachers must be prepared to negotiate with students the sometimes opposing worldviews that might exist between Indigenous knowledge systems and Western scientific methodologies in a tender and sensitive way. This requires creating a classroom environment that honors and values multiple perspectives and probes students to engage in critical thinking about truth and knowledge. Teachers engaging in professional learning opportunities focused on culturally responsive teaching and the incorporation of Indigenous knowledge in STEM education can get support in the challenging instructional moves.

Creating an ethno-STEM classroom with the PAPEDA framework mandates educators to stay open-minded, cutting-edge, reflective, and adept. By committing to an approach that values each of these dispositions, educators can cultivate dynamic and culturally rich learning environments that allow students the opportunity to engage in purposeful and connected STEM learning experiences - to bridge the gap between traditional knowledge and contemporary innovations in science.

Whereas PAPEDA emerged from a specific cultural situation, it lends itself to adaptations that can work in different settings around the globe. Capturing its workings within some cultural frameworks is essential for global uptake and effectiveness.

In East Asia, PAPEDA might be consistent with existing orientations towards collective learning and traditional wisdom. In places such as Japan or Korea, the framework might accommodate traditional ecological knowledge on sustainable agricultural practices or traditional mathematical ideas in architecture when adjusted to the more organized educational orientations in such cultures (Matsushita et al., 2023; Min & Lee, 2019). Notably, its emphasis on community engagement would echo the East Asian values of collective knowledge and transmission of knowledge from older to younger generations.

In levels of education within Africa, PAPEDA might be adapted with the addition of the rich traditions of oral history and indigenous technological practices. This framework presents an excellent opportunity to go ahead with education in some areas where traditional knowledge in agriculture, medicine, and astronomy is still strong but is often severed from formal education (Funteh, 2015; Mawere, 2014). For instance, in the East African region, PAPEDA may use traditional methods of weather prediction meshed up with modern meteorological science, or combine traditional conservation practices with modern-day environmental science.

PAPEDA might truly build upon existing efforts facing similar challenges in Latin America around preserving indigenous knowledge systems to leap forward in technological education. The framework would find particular traction in countries with strong indigenous populations, including Mexico and Peru, where elements like traditional agricultural practices, architectural techniques, and mathematical concepts might already have existed and can now be absorbed into modern STEM education efforts (Cole & O'Riley, 2017; Parra et al., 2016). The emphasis of PAPEDA on community working together finds strong common ground with traditions of shared learning and shared knowledge in Latin America (Zidny et al., 2021).

However, successful adaptations across these diverse settings require careful attention to many factors:

1) Local Cultural Protocols

The framework must be tuned to respect specific cultural protocols regarding knowledge transmission and community authority structures.

2) Educational Systems

Implementation must take existing educational structures and requirements into account while holding true to the core principles of the framework.

3) Resource Availability

Such adaptations must factor in that contexts vary in access to technological and material resources.

4) Cultural Preservation

Preservation of culture must somehow be maintained within this flexible framework by being adapted to various cultural settings and needs.

This global adaptability of PAPEDA suggests a flexible model for culturally responsive STEM education that can work worldwide, allowing us an insight into the notion that this flexibility needs to be instituted carefully, with attention to each setting's specific context.

7. Limitations and Challenges in PAPEDA Framework Conceptualization

The design of the PAPEDA framework is, in concept, one of the new approaches to the ethno-STEM approach. However, it does come with certain reservations that must be considered. Knowledge of such shortcomings would constitute essential information for consideration during the implementation and further development of the framework.

A significant challenge faced in implementing PAPEDA is cultural competence. Many teachers feel uncomfortable simply because they are unfamiliar with the cultural content they are being asked to integrate, leading to fears of cultural appropriation and misrepresentation (Aslam et al., 2023; Shernoff et al., 2017). This challenge is particularly acute in culturally diverse classrooms, while also burdening educators with many different cultural perspectives. The requirement for ongoing consultation with community knowledge holders, while an important prerequisite for authentic engagement, also means that a significant amount of time and effort must be devoted to the teaching process.

Difficulties of authentic cultural representation also pose another limitation. While PAPEDA attempts to integrate cultural knowledge with STEM education, this inherently carries the risk of incorporating superficial or merely lip service cultural elements. The introduction of the framework may not fully capture the holistic and interlinked nature of Indigenous knowledge systems, given that other traditional knowledge systems are embedded in fundamental spiritual or cultural practices that defy systematic categorizing.

Implementation of PAPEDA framework in different cultural contexts raises questions of standardization. Although this framework tries to be as flexible as possible, it cannot be said that its structure would fit all cultures. By imposing a one-dimensional model on culturally diverse contexts, the whole concept of cultural responsiveness the framework tries to promote may be weakened.

The limitations arising from teacher preparation pose considerable constraints (Jekri & Han, 2020; Okechukwu & Gabriel, 2014). The framework assumes there will be educators who have expertise in STEM subjects, as well as cultural knowledge-- a situation that rarely occurs in real life in many cases. The challenge of preparing teachers to implement the framework truly and spotting that cultural authenticity is demanding; however, it has to be done.

Limited resources and training often hinder the successful implementation of the framework. Many teachers lack access to culturally appropriate teaching materials, adequate professional development, and adequate mentorship from experienced practitioners (Leung, 2023). Lack of time to integrate culture and cultural considerations into lessons is a major concern given the demands of routine teaching. In addition, lack of funding means that cultural activities and field experiences may not occur, limiting the opportunities for deep learning envisioned by the framework.

The many aspects of the framework concerned with technological integration may become moot in communities that lack proper access to modern technology or in situations where traditional knowledge is passed on through alternative forms of transmission(Sabo et al., 2022). This will create an opportunity for differences in potential educational settings with regard to their implementation ability.

The assessment component presents yet another area of challenge. The dual focus on STEM learning outcomes and cultural knowledge preservation complicates the development of appropriate assessment tools. The depth of cultural learning, possibly not caught by the scope of teacher-led assessments available in classic education, puts up a question on standardizing the assessment of cultural knowledge without compromising its authenticity.

Effective PAPEDA implementation requires comprehensive teacher training that combines cultural immersion experiences, STEM integration workshops, and ongoing mentorship programs. Professional development should focus on cultural competency, practical teaching strategies, and community engagement skills (Estapa & Tank, 2017). Regular collaboration with cultural knowledge holders and experienced PAPEDA practitioners ensures continuous learning and authentic implementation. Structured feedback systems and peer support networks help teachers adapt and refine their approaches over time.

PAPEDA thus embodies an educational innovation whereby it serves as a development model for how a society might try to meet the challenge of preserving cultural knowledge and advancing scientific knowledge. Its global implications suggest that education could be reformed, honoring both the traditional and the modern, thus creating greater avenues for inclusive and effective education worldwide. PAPEDA, through this integration of diverse knowledge strands, while preserving cultural integrity, can provide significant insights for educators, policymakers, and communities around the world, even as the education systems evolve in response to global challenges.

8. Future Directions and Research Opportunities

The economic and attention-policy consequences of implementing PAPEDA within educational systems reach far beyond the immediate educational consequences.

This initial economic investment extends into such areas as: teacher training demand great resources in order to develop and prepare teachers in the field concerning STEM content application, cultural-integrative methodologies creation and curriculum development to create materials that are culturally based and in compliance with traditional knowledge and contemporary standards of STEM, and perhaps some infrastructure modification to support technical integration and community learning spaces that the framework embraces.

Broader policy implications include Indigenous peoples' rights policies regarding the protection and use of cultural knowledge, research funding strategies to support documentation and validation of traditional knowledge, economic development policies recognizing the role traditional practices play in fostering innovation, environmental policies because of traditional ecological knowledge use, and cultural preservation policies connecting education with heritage conservation.

However the PAPEDA framework is an important initial approach to thinking ethno-STEM that opens up many interesting areas for additional research. One of them is significant, long-term ways to understand the impacts of applying a PAPEDA's more ethno-STEM-friendly approach to youth learners. For example, future studies could use longitudinal designs with ethnically and culturally diverse young learners to gain insight into whether ethno-STEM approaches with the PAPEDA model impact student gains in STEM engagement, educational achievement, and career selection.

Validation of the PAPEDA framework is requested through extensive, combined theoretical and methodological approaches. The evaluation of effectiveness, reliability, and appropriateness for use in a variety of pedagogical contexts should be conducted using qualitative and quantitative research techniques, as this would provide in-depth data for understanding the impact and functionality of the framework.

The vetting process through peer review and expert evaluation will provide recommendations on the theoretical soundness and practical applicability of the framework. It also could involve reviews by experts in the fields of STEM approaches, cultural studies, knowledge systems for Indigenous peoples, and practitioners with experience in implementing similar constructs.

The teachers conducting action research while utilizing the PAPEDA framework will provide dramatic insights into how it works practically. This research should focus on documenting the entire process of implementation, specifying challenges and solutions, and assessing the fluidity of the framework in different educational contexts. Teachers' reflections and professional development outcomes would offer rich data to the usability and efficacy of the framework from the teaching perspective.

Moreover, the analyses of case studies that have been positively implemented will generate extensive examples of how the framework works in a certain context. The studies will reflect on both the implementation process and its outcomes to complement rich descriptions that may be useful toward future applications. Multiple case studies of various contextual and educational locales give credence to the framework's generalizability and openness to adaptation.

Another possible avenue would be to examine whether the PAPEDA's more ethno-STEM-friendly approach increases student persistence in STEM fields, students' cultural pride, or students' capacities to innovate within their communities. These could be used to continue to investigate and measure whether there are educational equity trends identified through exposure to PAPEDA, or trends that successively diversify the representation of underrepresented ethnic and cultural groups in STEM fields.

Furthermore, another important area for future work would be the adaptability of the PAPEDA's more ethno-STEM-friendly approaches to different cultural contexts. While the PAPEDA model has shown promise in some studies, its effectiveness will likely fluctuate depending on the cultural context within which it is applied. A cross-cultural investigation into the use of the PAPEDA framework might also provide information about the generalizability of PAPEDA across cultural contexts and also begin to suggest modifications that might be needed or considerations for different cultural settings that would need to be considered in future implementations. This potential area of research could be extended further to guide how PAPEDA could be modified most effectively for use in different cultural contexts while maintaining the high-level conceptual cultural lens of PAPEDA. A third emerging, somewhat interesting question would be about how to think about this PAPEDA framework in multicultural classrooms wherein the learners have multiple different cultural backgrounds.

The framework provides a strong foundation for thinking about how to incorporate exciting new technologies into practice with PAPEDA framework in ethno-STEM. With the advancements in educational technology, there exist chances to improve each stage of the PAPEDA process through the use of digital tools. For example, virtual and augmented reality could be utilized to design immersive cultural experiences in the "Provide" stage, and artificial intelligence could support the "Analyze" stage in ways such as aiding students in interpreting complex scientific and cultural information. Inquiry into how we may use these technologies while also prioritizing the cultural authenticity that is foundational to ethno-STEM to advance diverse educational practices.

There is also a need for more research on assessment that aligns with the eclectic character of the PAPEDA framework. Traditional assessment methods may not be sufficient to encapsulate the diverse outcomes of ethno-STEM approaches, such as the embodiment of cultural reciprocity, and the ability to synthesize diverse arrays of knowledge systems and their impact on communities. It is necessary to develop and validate alternative means of assessment that can evaluate these diverse outcomes alongside traditional STEM competencies in order to further the public dissemination and legitimacy of PAPEDA-based curricula.

A potentially rich area for future inquiry is the capability of the PAPEDA framework to contribute to sustainable development and concurrently address global challenges by engendering locally relevant solutions. Research could explore how ethno-STEM projects initiated through PAPEDA can support pragmatic solutions to real-world challenges such as environmental conservation, public health, and sustainable agriculture. This area of investigation could not only showcase the pragmatic relevance of ethno-STEM approaches but also underscore the importance of preserving and pairing conventional knowledge in the face of addressing issues facing society.

Moreover, investigating the potential of the PAPEDA framework to facilitate interdisciplinary learning opens up another exciting area of inquiry. As real-world problems necessitate solutions that often require input from multiple disciplines, understanding how PAPEDA might be used to connect STEM fields with other domains such as social sciences, arts, and humanities could lead to participatory and innovative educational initiatives.

Finally, research on teacher education and professional development to support the implementation of PAPEDA is essential. Possible research questions could include: What skills and knowledge are necessary for educators to integrate cultural knowledge into STEM instruction with PAPEDA, and what types of professional development will be most helpful? This work can help to inform the development of specific teacher education programs, and ongoing teacher professional development experiences, that will equip educators with the skills necessary to implement ethno-STEM approaches with PAPEDA.

As this research is pursued, interdisciplinary collaboration among educators, culture bearers, STEM professionals, and community members will be needed. This is because ideally, this work should be grounded in scientific basis and in ethno-cultural authenticity, both of which can lead to significant advancements in ethno-STEM approaches, and ultimately lead to more inclusive and effective STEM learning experiences for all students across diverse contexts.

9. Conclusion

The emergence and evolution of the PAPEDA framework in ethno-STEM approaches represents a milestone in culturally responsive education whose impact transcends individual classrooms or communities. As we reflect on its journey from conception to implementation, the framework's potential to change global educational practice becomes increasingly evident.

In a world torn apart by the many challenges of education, PAPEDA enjoys a special status amidst the panorama of world cultures, with the respect and preservation of local cultures at the fore. Provided there are enough commitments to its full safeguarding, the PAPEDA framework runs the risk of preserving an ethnic balance simplified by generalization attributes. Meanwhile, it effectively steers culture in the right direction. Thus, the PAPEDA framework facilitates communication between local knowledge and modern STEM education in creating a highly conducive environment necessary for addressing an ever-growing global need for culturally responsive educational practice to become the norm rather than the exception.

Of special interest is the framework's contribution to sustainable development goals. By validating and preserving traditional ecological knowledge alongside modern scientific understanding, PAPEDA supports global efforts towards environmental sustainability and cultural preservation. The integration of traditional knowledge with contemporary science provides a special opportunity for education to tackle growing issues such as biodiversity conservation and climate change, with respect to both indigenous and modern knowledge systems.

The future of a PAPEDA-based ethno-STEM approach includes an abundance of opportunities to explore and research. Some questions go well beyond the types of analyses completed for this work including potential efficacy on student outcomes, its translation to different cultural contexts, how the technologies of today might have a role, and consideration for the diversity of ways in which students should be assessed for their learning. We intend to show how innovative and creative the opportunities are for those interested in developing the model and in understanding the integration of cultural knowledge and scientific learning to address world problems.

Ethical implementation of PAPEDA needs to be respectful of cultural values and intellectual property rights. It involves taking appropriate permissions for knowledge holders, giving proper recognition to traditional knowledge, giving values protection of cultural sensitive information, and accurately representing cultural practice. The framework must include community benefits without exploitation or misappropriation of indigenous knowledge.

The PAPEDA framework of ethno-STEM approaches is viewed as a significant advance in making STEM education more inclusive, relevant, and impactful. The model presents a vision of science education that honors the world's cultural diversity while expanding the scope of scientific inquiry, preparing students to be both culturally aware and globally competitive. As educators, researchers, and policymakers, the call is to examine, explore, implement, and expand the model. This allows for exciting opportunities to design educational experiences that teach STEM concepts and honor the multiplicity of human knowledge and experience.

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