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## Developing a Culturally Responsive Syntax for Physics Co-Curricular Activities: A Participatory Approach Integrating Local Wisdom

M. A. Martawijaya\* , Mahir  and Pariabti Palloan 

Department of Physics Education,  
 Makassar State University, Indonesia

**Abstract.** In recent years, increasing attention has been given to culturally responsive Science, Technology, Engineering and Mathematics education due to the need to connect scientific learning with students' socio-cultural experiences. This study developed and validated MAGUSM (*Minasa-Ada-Gau-Uki-Sabbi-Mabbarakka*), a culturally responsive syntax for physics co-curricular activities that integrates Bugis-Makassar local wisdom through a participatory design approach. It addressed the underrepresentation of cultural perspectives in science education despite global demands for 21st-century competencies such as collaboration, critical thinking, creativity, and cultural awareness. Fourteen participants, prospective and in-service teachers and education practitioners, co-designed and refined the syntax through consensus-building, prototyping, focus group discussions (FGDs), and laboratory trials. Data were collected using validation sheets and analyzed with Aiken's V, supported by thematic analysis of interviews and observations. Results indicated that MAGUSM is valid and feasible, with all components rated "very feasible" (mean Aiken's V = 0.87). Scores improved across syntax stages from FGD I to FGD II, particularly in the *Gau* stage. Integrating *a'bulo sibatang* (collective solidarity) enhanced collaboration, minimized conflict, and increased motivation by linking physics concepts with cultural practices. The syntax operationalized deep learning through understanding (*Minasa-Ada*), application (*Gau-Sabbi-Uki*), and reflection (*Mabbarakka*). Theoretically, this study extends deep learning pedagogy with cultural dimensions, while practically offering a replicable framework for fostering 21st-century skills despite limitations in sample size and laboratory scope.

**Keywords:** culturally responsive pedagogy; deep learning; local wisdom; participatory design; physics co-curricular activities

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\*Corresponding author: M. A. Martawijaya; [martawijayamagus@unm.ac.id](mailto:martawijayamagus@unm.ac.id)

## 1. Introduction

Recent studies on culturally responsive Science, Technology, Engineering and Mathematics (STEM) education emphasize that Indigenous knowledge systems remain underrepresented within science learning frameworks despite increasing global advocacy for contextualized learning environments (Govender & Mudzamiri, 2022; Harrison & Skrebneva, 2020; Pang et al., 2021). Competencies such as collaboration, critical thinking, creativity, problem-solving, and cultural awareness are consistently highlighted by UNESCO and the OECD as indispensable for preparing students to navigate globalization, technological change, and social complexity (Addey, 2021; Bravo et al., 2021; Kasa et al., 2023).

Within this context, science education, and physics in particular, play a central role due to their emphasis on inquiry, experimentation, and conceptual reasoning (Abaniel, 2021; Banda & Nzabahimana, 2021; Ogegbo & Ramnarain, 2022). However, despite global recognition of these priorities, there remains limited understanding of how to systematically embed cultural perspectives in science learning. While deep learning frameworks have been widely examined in Western contexts, few studies have investigated how Indigenous cultural values can be integrated into co-curricular science activities, leaving an essential gap in the literature (Chang et al., 2022; Harrison & Skrebneva, 2020; Lim et al., 2019).

At the same time, developing countries, including Indonesia, face persistent challenges in ensuring that learning is meaningful, contextual, and culturally relevant. The digital era creates significant opportunities for innovation, yet it also accentuates gaps between students who can adapt and those who are left behind (Blomkamp, 2022; Spinuzzi, 2005). Strengthening collaboration and critical thinking, therefore, demands systematic pedagogical approaches that bridge disciplinary knowledge, 21st-century skills, and socio-cultural relevance. International research increasingly shows that participatory and collaborative learning designs offer one such pathway, as they involve learners, teachers, and communities as co-creators of knowledge rather than passive recipients (Blomkamp, 2022; Spinuzzi, 2005).

Empirical evidence underscores the importance of this direction. Collaborative learning has been shown to foster both cognitive gains and social skills (Almulla & Al-Rahmi, 2023; Qureshi et al., 2023; Xu et al., 2023), while explicit critical thinking instruction improves reasoning and decision-making (Bayat et al., 2022; Ho et al., 2023; Teng & Yue, 2023; Tursynkulova et al., 2023). Deep learning approaches, which emphasize understanding, application, and reflection (Wang et al., 2024; Weng et al., 2023; Zhang et al., 2024), provide a strong pedagogical framework for integrating these skills. Yet, most existing research treats deep learning as a cognitive process, without incorporating cultural dimensions that could make it more socially meaningful (Fan et al., 2021; Fitriani et al., 2020; Ünal, 2019; Wang et al., 2024). This is a limitation not only in Indonesia but across Southeast Asia, where culturally diverse societies have rich traditions that could be mobilized for science learning.

In the Indonesian context, the urgency of addressing these gaps is reflected in both national policy and student outcomes. Policy frameworks such as the 2013 Curriculum and the Independent Curriculum emphasize the integration of 21st-century skills and character education into curricular and co-curricular learning (Puad & Ashton, 2023; Warman et al., 2021). Nevertheless, results from PISA 2022 show that Indonesian students remain below the OECD average in literacy, numeracy, and scientific reasoning (El Islami et al., 2022; Mukhlis et al., 2023). Particularly concerning are deficits in higher-order problem-solving and collaborative reasoning, which limit students' ability to participate in global knowledge economies. These conditions underscore the need for innovative, culturally grounded approaches that can strengthen collaboration and critical thinking in ways that resonate with learners' lived experiences.

Co-curricular activities provide a promising arena for addressing these challenges because they offer flexible, authentic spaces to apply knowledge and skills beyond the classroom (Cruz et al., 2024; Jackson et al., 2022; Olewnik et al., 2023; Sukadari & Huda, 2021). Internationally, well-designed co-curricular programs have been found to support socio-emotional development, leadership, academic performance, and learning satisfaction (Martawijaya et al., 2025). Yet in Indonesia, physics co-curricular activities often remain fragmented, loosely connected to curricular goals, and underuse local cultural resources. This gap suggests untapped opportunities to both enrich students' scientific experiences and foster a stronger sense of cultural identity.

Previous studies have explored culturally responsive pedagogy in science education and co-curricular learning; however, most studies focused either on integrating cultural artifacts into instruction or on general participatory learning frameworks without operationalizing Indigenous values into structured pedagogical syntax (Govender & Mudzamiri, 2022; Pang et al., 2021; Sugiantoro et al., 2022). Moreover, existing deep learning models predominantly emphasized cognitive dimensions and rarely incorporated Indigenous ethical and collaborative values into STEM co-curricular activities. This gap motivated the development of MAGUSM.

Integrating local wisdom provides a valuable pathway for this. Local wisdom refers to community-based values, knowledge systems, and practices transmitted across generations and often serve as ethical and collaborative foundations for social life (in Indonesia, Bugis-Makassar traditions offer vibrant resources). Values such as *siri' na pacce* (dignity and empathy), *getteng* (consistency), *reso* (hard work), and especially *a'bulo sibatang* (collective solidarity) align directly with the goals of 21st-century education (Martawijaya et al., 2023; Martawijaya et al., 2025). These values not only sustain cultural identity but also map onto internationally recognized dimensions of collaborative and participatory learning (Gkonou & Miller, 2021; Wright et al., 2022). Importantly, similar opportunities exist in other cultural contexts, such as Māori education in New Zealand or Indigenous education in Canada, highlighting the global significance of such integration.

To date, however, no model has systematically combined deep learning pedagogy with Indigenous cultural norms in physics co-curricular contexts. Most existing approaches either treat cultural elements as supplementary content (e.g., folklore, artifacts) or adopt top-down designs with limited stakeholder participation (Govender & Mudzamiri, 2022; Pang et al., 2021; Sugiantoro et al., 2022). As a result, many models remain unsustainable and lack broad acceptance in practice. Addressing this gap, the present study introduces MAGUSM, a participatory syntax of physics co-curricular activities developed collaboratively with prospective teachers, in-service teachers, and education practitioners.

The novelty of this research lies in three aspects: (1) positioning diverse stakeholders as active co-creators in the design process, (2) embedding *a'bulo sibatang* values as a structural core rather than as an add-on, and (3) demonstrating the potential for global transferability of culturally responsive co-curricular models. Accordingly, the study pursued three objectives: to design and develop a participatory syntax for physics co-curricular activities rooted in local wisdom, to refine and validate the syntax through collaborative evaluation, and to examine its capacity to strengthen collaboration and critical thinking. Theoretically, the study expands participatory curriculum design by integrating cultural frameworks into deep learning pedagogy. In practice, it provides teachers and policymakers with a replicable model for cultivating 21st-century skills across diverse educational settings.

## 2. Methods

### 2.1 Research Design

This study employed a participatory design approach, positioning prospective teachers, teachers, and practitioners as co-creators in developing the syntax of physics co-curricular activities (Spinuzzi, 2005). This approach was selected to ensure that the resulting model was not only academically robust but also culturally relevant and practically applicable (Smith et al., 2017). Participatory design emphasizes reflective dialogue, knowledge exchange, and collective decision-making, which increase social validity and acceptance (Blomkamp, 2022; Broomfield et al., 2021; De Vente et al., 2016; Slingerland et al., 2022; Udoewa, 2022).

### 2.2 Research Participants

Fourteen participants were selected purposively based on three criteria: (1) prior involvement in physics teaching or curriculum development, (2) familiarity with co-curricular learning practices, and (3) understanding of Bugis-Makassar cultural values. Prospective teachers were selected from final-year students who had completed teaching practicum experiences, while in-service teachers had a minimum of five years of teaching experience. Given the exploratory nature of the study, the number of participants (N=14) was intentionally limited to allow intensive dialogue and iteration. This small sample, while sufficient for initial model validation, restricts the generalizability of findings and should be addressed in future research with broader classroom-based implementations. Prospective teachers were involved in generating initial design ideas, teachers,

as key implementers, and practitioners to provide perspectives on curriculum and policy (Ahmad & Wilkins, 2025; Staller, 2021). The study was conducted at a state university in South Sulawesi in collaboration with partner schools. The Bugis–Makassar context was chosen because the cultural norm of *a'bulo sibatang*, which emphasizes solidarity and collective responsibility, served as the ethical foundation for the developed syntax.

### 2.3 The Development Process of MAGUSM Followed an Iterative Four-Stage Cycle

- a) Consensus-building: Researchers facilitated discussions with stakeholders to explore needs and expectations for a co-curricular syntax.



Figure 1: Consensus-building stage with practitioners

- b) Initial design: Prospective teachers drafted the MAGUSM syntax by combining literature on deep learning, Bugis–Makassar cultural values, and local phenomena. The draft included seven stages: Pre-Syntax, *Minasa*, *Ada*, *Gau*, *Uki*, *Sabbi*, and *Mabbarakka*.

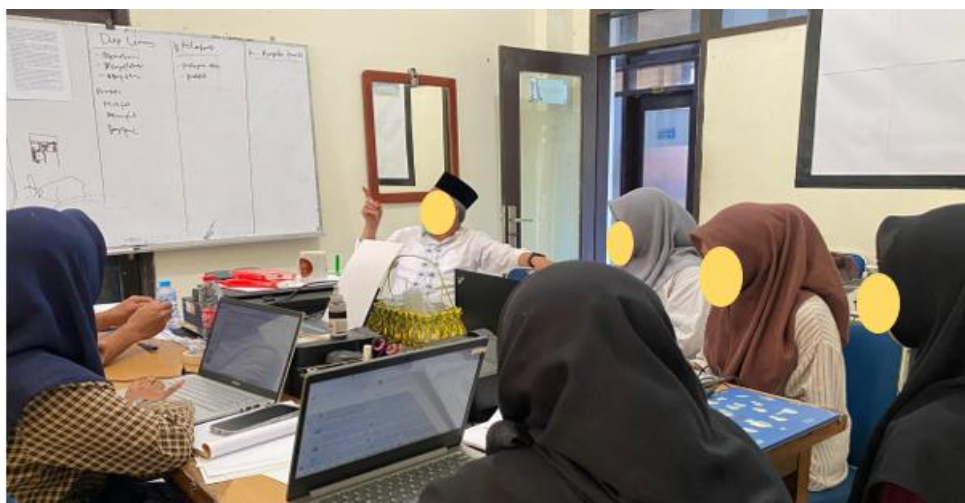
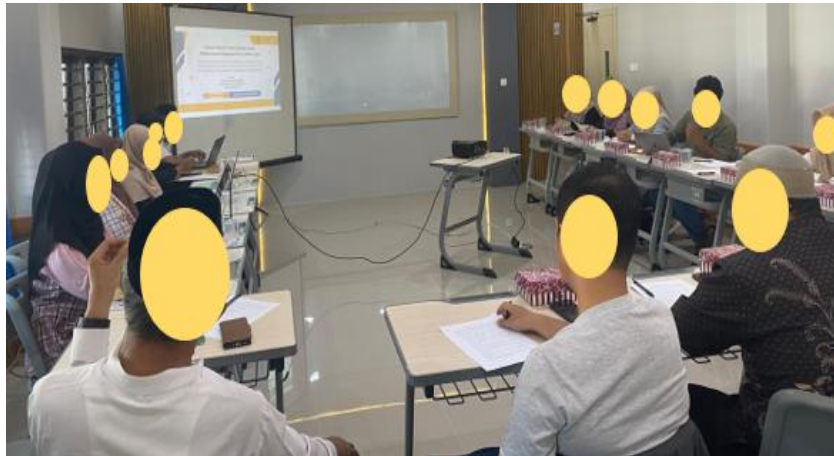


Figure 2: Initial draft of the MAGUSM syntax

- c) First FGD: The draft was presented to teachers and practitioners for feedback on clarity, cultural integration, curricular alignment, and feasibility.



**Figure 3: The first FGD on the syntax design of MAGUSM**

- d) Revision and laboratory trials: The syntax was refined based on FGD input and tested in a laboratory setting.



**Figure 4: Revision and retrieval of laboratory data**

- e) Second FGD: The revised syntax was validated with stakeholders, focusing on feasibility, clarity, integration of *a'bulo sibatang* values, and potential to foster collaboration and critical thinking.



Figure 5: The second FGD on syntax validation MAGUSM

## 2.4 Instruments and Data Collection

The instruments used in the collection of research data were as follows.

- 1) Quantitative: The validation sheet consisted of 25 items distributed across five dimensions: syntax clarity, cultural integration, deep learning alignment, curricular relevance, and implementation feasibility. Items were developed based on previous validation studies and culturally responsive pedagogy frameworks (Sass et al., 2021; Scott et al., 2021; South et al., 2022). Item complexity ranged from simple evaluative indicators to integrative indicators requiring holistic judgments regarding pedagogical alignment. Prior to implementation, the instrument underwent expert review involving two curriculum experts and one educational measurement specialist to establish content validity and readability.
- 2) Qualitative: Semi-structured interviews were used to explore participant perceptions regarding cultural relevance, implementation feasibility, and pedagogical effectiveness. FGD protocols were designed to facilitate collaborative critique and reflective dialogue among stakeholders. Observation sheets documented participant interactions, communication patterns, and collaborative engagement during laboratory trials (Geampana & Perrotta, 2025; Panyasai & Ambele, 2025).
- 3) Documentation: Audio recordings and transcripts supported the analysis (Geampana & Perrotta, 2025; Panyasai & Ambele, 2025).

## 2.5 Data Analysis

Quantitative data were analyzed descriptively (means, standard deviations, eligibility categories) and with Aiken's V to determine inter-rater consistency (Kreitchmann et al., 2024; Roebianto et al., 2023). Qualitative data underwent thematic analysis involving data reduction, coding, categorization, and interpretation (Lochmiller, 2021; Morgan, 2022; Nicmanis, 2024). Results from both strands were integrated to provide a comprehensive picture of the syntax's validity and feasibility.

### 3. Results and Discussions

This research resulted in a syntax of local culture-based co-curricular physics activities called MAGUSM. This syntax was developed through a participatory approach by involving prospective teachers, physics teachers, and education practitioners as co-creators. Validation was carried out using quantitative instruments and focus group discussion forums (FGDs), which were carried out in two stages. In general, the results of the study show that the MAGUSM syntax and its supporting tools are considered very feasible in terms of stage clarity, integration with Bugis–Makassar cultural values, relevance to deep learning-based learning, and feasibility of implementation in the context of physics co-curricular activities (see Table 1).

**Table 1: MAGUSM Syntax and Tool Validation Recapitulation**

No	Syntax Aspects	Mean	SD	Category
1	Syntax Stages	0.87	0.02	Very Feasible
2	Kapita Student Selection Book	0.86	0.02	Very Feasible
3	Student Worksheets	0.86	0.04	Very Feasible
4	Teacher's Handbook	0.86	0.02	Very Feasible
5	Collaboration Skills Instrument	0.93	0.13	Very Feasible
6	Critical Thinking Skills Instrument	0.86	0.02	Very Feasible
	<b>All Aspects</b>	0.87	0.03	Very Feasible

The high feasibility scores align with previous studies, indicating that culturally responsive and participatory STEM models enhance contextual relevance and stakeholder acceptance (Portillo-Blanco et al., 2024; Sillaots et al., 2023). Similar findings are reported by Govender and Mudzamiri (2022), who found that integrating Indigenous perspectives into physics education increased learner engagement and collaborative participation.

The validation results show that all aspects of the syntax and its supporting tools are categorized as very feasible, with an average Aiken's V score of 0.87 and a standard deviation of 0.03 (see Table 2). The highest-scoring aspect was the collaboration skills instrument with a value of 0.93, indicating that the integration of collaboration principles in syntax is very strong. Other devices, such as Kapita Selecta books, student worksheets, teacher handbooks, and critical thinking skills instruments, also received high scores, in the range of 0.86 to 0.87. This indicates that MAGUSM is designed not only at a conceptual level but also with supporting devices ready to be used by teachers and students.

**Table 2: Average Assessment of FGD I Participants on MAGUSM Syntax Activities**

No	Syntax Activity	Mean	SD
1	Pre-Syntax	8.00	0.37
2	<i>Minasa</i>	8.30	0.18
3	<i>Ada</i>	8.20	0.18
4	<i>Gau</i>	7.68	0.34
5	<i>Uki</i>	8.28	0.10
6	<i>Sabbi</i>	8.38	0.33
7	<i>Mabbarakka</i>	8.35	0.47

Furthermore, participants' assessment of MAGUSM syntax activities showed positive consistency of results (Table 3). In FGD I, the average score of the assessment ranged from 7.68 to 8.38. The level with the highest score was *Sabbi* (8.38), while the lowest score was found at the *Gau* level (7.68). Despite this, all grades remained in the excellent category. These results indicate that from the early stages, the MAGUSM syntax has been assessed as clear and relevant, although there are notes of specific improvements in the *Gau* stage related to the clarity of the instructions and their connection to the critical thinking indicators.

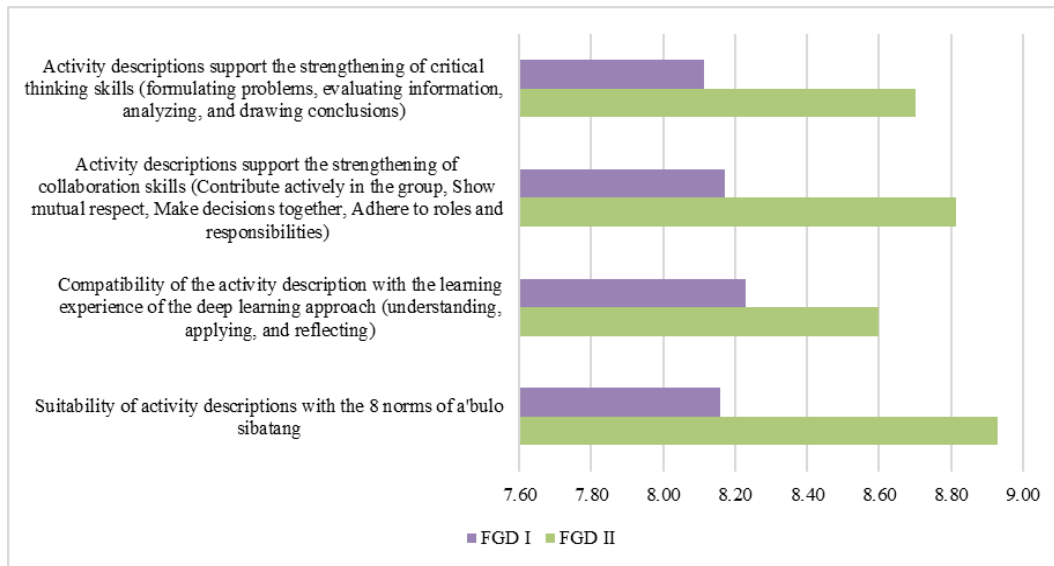
**Table 3: Average Assessment of FGD II Participants on MAGUSM Syntax Activities**

No	Syntax Activity	Mean	SD
1	Pre-Syntax	8.85	0.30
2	<i>Minasa</i>	8.73	0.22
3	<i>Ada</i>	8.63	0.21
4	<i>Gau</i>	8.80	0.16
5	<i>Uki</i>	8.78	0.17
6	<i>Sabbi</i>	8.83	0.13
7	<i>Mabbarakka</i>	8.73	0.10

After revision based on participant input, the reassessment was carried out through FGD II. The results showed an improvement in scores at all stages, with a score averaging between 8.63 and 8.85. The most significant increase occurred in the *Gau* stage, which previously obtained the lowest score but rose to 8.80 with a standard deviation of only 0.16. This indicates that improvements made according to participant input succeeded in increasing the clarity and feasibility of the stage. In general, the average FGD II score showed a higher number with a lower degree of variation, thus indicating the stability of the acceptance of the MAGUSM syntax.

When visually comparing the results of FGD I and FGD II, there appears to be a consistent improvement trend at all stages. The pre-syntax stage, which was previously valued at 8.00, increased to 8.85, while the *Gau* stage increased from 7.68 to 8.80. This difference shows the effectiveness of the revision process carried out in a participatory manner. Thus, it can be concluded that the MAGUSM syntax underwent a rigorous validation process and gained recognition from participants as a co-curricular physics learning model that is feasible.

The improvement observed between FGD I and FGD II (see Figure 2) reflects the iterative refinement principle emphasized in participatory design literature (Spinuzzi, 2005; Udoewa, 2022). Similar findings are reported by Sillaots et al. (2023), who argue that stakeholder involvement strengthens ownership and implementation feasibility in educational innovation. Moreover, the integration of *a'bulo sibatang* aligns with socio-cultural learning theory, which views learning as a socially mediated process grounded in collective interaction and shared cultural meaning. These findings also support previous studies on Indigenous STEM education, which demonstrate that culturally contextualized learning environments increase student engagement, collaboration, and reflective understanding (Govender & Mudzamiri, 2022; Harrison & Skrebneva, 2020).



**Figure 2: Comparison of the average Participant Assessment through FGD I and II**

Participants emphasized that the integration of the value of *a'bulo sibatang* at each stage makes this syntax unique and relevant to the local context. Teachers believed that this cultural value fosters cooperation among students and mitigates potential conflicts in group discussions. Education practitioners highlighted the syntax's alignment with the policy direction of the Independent Curriculum, which emphasizes 21st-century skills, especially collaboration and critical thinking. Meanwhile, the prospective teacher stated that although the initial *Gau* stage was still unclear, the revision carried out was able to enhance students' understanding of designing and analyzing experimental activities. Observations during implementation also showed that students were more enthusiastic about participating in activities because the physics material was associated with daily cultural practices through its syntax.

### 3.1 Thematic Analysis of FGD and Interview Data

Thematic analysis was conducted on FGD transcripts, interview responses, and observation notes using coding, categorization, and theme development procedures following Lochmiller (2021) and Morgan (2022). Four major themes emerged from the analysis.

#### 3.1.1 Theme 1: Cultural relevance enhances student engagement

Participants consistently stated that integrating Bugis–Makassar values made physics learning more meaningful and relatable. One teacher explained:

*“Students became more enthusiastic because the activities reflected situations and values familiar to their daily lives.”*

This theme indicates that culturally responsive design increased emotional connection and participation.

#### 3.1.2 Theme 2: *A'bulo sibatang* strengthens collaboration

Teachers and practitioners emphasized that collective solidarity reduced interpersonal conflict during group experimentation. One participant stated:

*“The principle of a’bulo sibatang encouraged students to help each other rather than compete individually.”*

This finding supports socio-cultural perspectives emphasizing collaborative learning through shared responsibility.

### *3.1.3 Theme 3: Iterative revision improves syntax clarity*

Participants in FGD I identified ambiguity in the Gau stage, particularly concerning experimental procedures and critical thinking indicators. After revision, participants reported that instructions became clearer and easier to implement.

### *3.1.4 Theme 4: Participatory design increases stakeholder acceptance*

Participants appreciated being actively involved in the design process. Several respondents explained that participation created a sense of ownership and strengthened confidence in implementation feasibility. Overall, the thematic findings complement the quantitative validation results by demonstrating that MAGUSM was perceived as culturally meaningful, collaborative, and pedagogically feasible. The results confirm that the MAGUSM syntax was highly valid and feasible, with strong stakeholder support.

The integration of *a’bulo sibatang* within MAGUSM can be situated within broader debates on Indigenous science and epistemologies, which emphasize relational accountability and community-grounded knowledge systems that contrast with conventional Western framings (McKinnon & Muth, 2024). Embedding such epistemic elements into pedagogical syntax does not merely localize content; it reconfigures the aims and processes of learning to foreground communal responsibility and reflexive practice. These findings reinforce existing literature that stresses the importance of multi-stakeholder participation in educational design to enhance relevance and acceptance (Décamps et al., 2021; Harkins, 2018; Sillaots et al., 2023).

These align with recent systematic reviews in integrated STEM education, pointing out that characteristics such as stakeholder engagement, cultural relevance, and local contextualization are among the core principles of effective designs (Portillo-Blanco et al., 2024). Similar international initiatives, such as Sulitest for sustainability literacy and participatory STEM innovations in Finland (Hyotynen & Keltikangas, 2015), demonstrate how collaborative approaches produce socially sustainable educational models. MAGUSM extends this tradition into the realm of culturally responsive co-curricular physics education. Nevertheless, while international parallels (e.g., Māori education, First Nations in Canada) illustrate the relevance of Indigenous integration, claims of global transferability remain tentative. Adaptation to other contexts will require re-interpretation of local values rather than direct adoption of MAGUSM syntax.

Deep learning frameworks emphasize the phases of understanding, application, and reflection (Rui et al., 2024; Weng et al., 2023). These phases are operationalized in MAGUSM through *Minasa-Ada* (understanding), *Gau-Uki* (application), and *Mabbarakka* (reflection). Unlike prior studies that treat deep

learning primarily as cognitive scaffolding (Fan et al., 2021; Hwang & Oh, 2021), MAGUSM demonstrates how local wisdom can deepen reflective phases by connecting learning to social and cultural responsibilities (Dahmen-Adkins & Peterson, 2025; Howell, 2021).

The integration of *a'bulo sibatang* norms further illustrates how Indigenous cultural frameworks enhance collaborative learning. Norms emphasizing solidarity, honesty, and shared responsibility directly strengthened student cooperation, particularly in the *Ada*, *Gau*, and *Sabbi* stages. This finding resonates with socio-cultural learning theory (Vygotsky) and recent work on cultural capital in education (Henrich & Muthukrishna, 2021; Tian et al., 2025). Importantly, it also parallels Indigenous education practices elsewhere, such as Māori collective learning in New Zealand or First Nations' land-based education in Canada, underscoring MAGUSM's global transferability.

The MAGUSM syntax demonstrates strong alignment with the development of 21st-century competencies through its interconnected and culturally responsive learning stages. Critical thinking was particularly fostered during the *Uki* stage, where students engaged in data interpretation, analytical reasoning, and reflective evaluation of experimental findings. Communication competencies emerged prominently in the *Sabbi* stage through scientific dialogue, collaborative presentations, and argumentation processes that encouraged students to articulate evidence-based explanations. Collaboration was embedded across the syntax, especially during the *Ada* and *Gau* stages, where collective planning, group experimentation, and shared problem-solving activities operationalized the value of *a'bulo sibatang* as a form of communal responsibility and participatory engagement.

In addition, creativity was stimulated during the *Gau* stage as students designed and modified experimental procedures based on contextualized cultural phenomena. These findings support contemporary perspectives that conceptualize 21st-century competencies as interconnected capacities developed through authentic, socially mediated, and culturally meaningful learning experiences rather than as isolated technical skills. This holistic alignment supports international calls for integrated skill development within culturally responsive pedagogy (Chang et al., 2022; Harrison & Skrebneva, 2020; Lim et al., 2019). Theoretically, the study contributes by expanding deep learning theory with cultural dimensions, showing that reflection is not only cognitive but also ethical and communal. Practically, MAGUSM offers a replicable model for teachers seeking to integrate local wisdom with STEM pedagogy, while for policymakers it illustrates how participatory design can inform curriculum reforms.

#### **4. Limitations of the Study**

Several limitations should be acknowledged in interpreting the findings of this study. First, the number of participants involved in the participatory design process was relatively small and purposively selected, which may limit the broader generalizability of the findings. Second, the implementation and

validation of the MAGUSM syntax were conducted primarily within laboratory-scale trials rather than full classroom implementation, meaning that the dynamics of larger and more diverse learning environments were not fully captured. Third, the syntax was developed within the specific socio-cultural context of Bugis–Makassar local wisdom, particularly the value of *a'bulo sibatang*, which may require contextual adaptation before implementation in other cultural settings. Finally, the study focused mainly on feasibility and validity aspects and did not yet examine long-term impacts on students' academic achievement or sustained development of 21st-century competencies. Future studies are therefore needed to test the effectiveness, scalability, and cross-cultural adaptability of the MAGUSM syntax in broader educational contexts.

### **5. Implications and Recommendations**

The findings of this study provide several important implications for culturally responsive STEM education. Theoretically, the study contributes to the development of deep learning pedagogy by demonstrating that reflective and collaborative learning processes can be strengthened through the integration of Indigenous cultural values within co-curricular science activities. The MAGUSM syntax also extends participatory design approaches by positioning teachers, prospective teachers, and practitioners as active co-creators in educational innovation processes.

Practically, the findings suggest that culturally grounded co-curricular models may support the development of collaboration, communication, and critical thinking skills in more contextually meaningful ways. The integration of *a'bulo sibatang* values into collaborative physics activities showed potential for strengthening collective responsibility and student engagement during scientific inquiry processes. Therefore, educators and curriculum developers may consider incorporating local cultural frameworks into STEM learning designs to improve contextual relevance and learner participation.

Nevertheless, recommendations for broader implementation should be approached cautiously due to the limited scope of the present study. Future research is recommended to conduct classroom-based experimental implementation involving larger and more diverse participant groups. Further studies may also investigate the long-term effects of the MAGUSM syntax on students' higher-order thinking skills, learning motivation, and socio-cultural competence. In addition, comparative cross-cultural studies are needed to examine how the participatory and culturally responsive principles of MAGUSM can be adapted within different Indigenous or local knowledge contexts.

### **6. Conclusion**

This study addressed the limited integration of cultural perspectives within physics co-curricular learning by developing and validating MAGUSM, a participatory and culturally responsive syntax grounded in Bugis–Makassar local wisdom. The findings demonstrate that MAGUSM achieved strong validity and feasibility through iterative collaboration among prospective teachers, in-

service teachers, and educational practitioners. Quantitative validation and thematic qualitative analysis consistently showed that the syntax successfully integrates deep learning processes with cultural values such as *a'bulo sibatang*, thereby strengthening collaboration, critical thinking, and student engagement. The study contributes theoretically by extending deep learning pedagogy beyond cognitive dimensions toward ethical, communal, and culturally responsive learning processes. Practically, the findings provide educators and policymakers with a replicable framework for designing co-curricular STEM activities that connect scientific inquiry with local cultural contexts.

The participatory design process also demonstrates the importance of stakeholder collaboration in developing sustainable educational innovations. Despite limitations related to sample size, laboratory-scale implementation, and cultural specificity, the findings remain significant as an exploratory model for culturally grounded science education. Future research should expand implementation into broader classroom contexts, involve more diverse participants, and adapt the syntax across different cultural settings. Ultimately, MAGUSM illustrates that integrating Indigenous values into STEM education can support globally relevant, socially sustainable, and culturally meaningful learning experiences.

#### **Conflict of Interest**

The authors declare no conflict of interest in the study and acknowledges the Philippine Normal University-Manila for its support.

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#### **9. Gen-AI Tools Declaration**

ChatGPT (OpenAI, 2026) and Grammarly (Grammarly Inc., 2026) were used to refine the language and grammar of the manuscript. The authors performed all research design, data analysis, and interpretations.

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