

When Ancient Epistemology Meets Augmented Reality: Designing a STEM–Catur Pramana Digital Pop-Up Book for Elementary Science

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Abstract

Elementary science learning in Indonesia often relies on text-heavy materials, and efforts to bring local culture into science education have mostly treated culture as content rather than as a way of knowing. This study designed and validated an augmented reality (AR)-assisted digital pop-up book that uses Catur Pramana, the four means of valid knowledge in Hindu philosophy, to structure STEM-based learning. Direct observation, inference, comparison, and reliable testimony were paired with mathematics, technology, engineering, and science, respectively, across three topics: plant growth and reproduction, states of matter, and forces. Following the ADDIE model, a prototype without AR was tried out with 86 students and 15 teachers in four public elementary schools in Bali, Indonesia, and then revised into a final version with AR features, which three content experts and three media experts evaluated. Content and media validity were moderate (Aiken's $V = 0.74$ and 0.78), with the weakest ratings for curriculum alignment, the engineering and mathematics components, and the stability of AR objects, and agreement among the experts was moderate (intraclass correlation = 0.71 and 0.72). Students and teachers rated the prototype as practical (73.40% and 77.50%). The findings show that a local epistemology can serve as the structure, not merely the content, of a science learning medium. Because AR was not part of the classroom tryout and learning outcomes were not measured, the results establish the feasibility of the design rather than its effectiveness.

1 Introduction

Inquiry is widely regarded as central to science education [1]. Through inquiry, students are expected not only to acquire scientific knowledge but also to engage in the processes that produce it, such as observing, inferring, comparing, and communicating evidence. National performance indicators, however, suggest that these aims are not yet fully realized. In PISA 2025, which focused on science, Indonesian students obtained a mean science score of 389, well below the OECD average of 482, and only 37% reached the baseline level of science proficiency, compared with 74% across OECD countries [2]. Part of the problem lies in classroom practice. Indonesian science classrooms have long been characterized by teacher-centred instruction in which students mainly listen and copy notes [3]. At the elementary level, teachers also report that many topics are abstract, that textbooks depend on two-dimensional illustrations, and that not every concept can be demonstrated through hands-on activities [4]. When technology is integrated with inquiry-oriented instruction, primary pupils tend to show better conceptual understanding, stronger scientific thinking skills, and higher motivation [5]. Programs that combine technological resources with classroom teaching have also shown positive effects on elementary science achievement [6]. Learning media that make abstract phenomena observable, while guiding students through the reasoning processes of science, therefore deserve closer attention.

Augmented reality (AR), which overlays virtual objects onto the learner's physical surroundings in real time, has become one of the most widely studied technologies for addressing these difficulties. Across 64 quantitative studies involving 4,705 students, AR produced a medium effect on learning gains ($d = 0.68$) [7]. A larger synthesis of 134 (quasi-)experimental studies published between 2012 and 2021

found that AR benefited learners' responses, such as motivation and attitude, as well as their knowledge, skills, and performance [8]. A review of AR in mathematics education likewise reported positive outcomes across studies, including greater engagement and enjoyment [9]. In STEM subjects, most AR applications have been designed to support exploration or simulation, allowing students to examine objects and processes that cannot easily be observed in the classroom [10]. Similar potential has been reported in Indonesian elementary schools, where an AR-integrated science book was associated with a high gain in students' science process skills [4]. Whether this visual advantage translates into deeper scientific reasoning, however, depends largely on how the learning experience around AR is designed.

The format in which such visualizations are delivered also matters. Digital pop-up books combine the three-dimensional appeal of paper pop-up books with narration, animation, and embedded video. A meta-analysis of 43 studies involving 2,147 children found that multimedia features such as animated pictures, music, and sound effects were beneficial, whereas interactive elements such as hotspots and games tended to distract [11]. These findings are consistent with the cognitive theory of multimedia learning, which holds that learners process pictorial and verbal information through separate channels, each with limited capacity [12]. Accordingly, pictures accompanied by spoken explanations generally produce better learning than pictures accompanied by on-screen text [13]. When narration is combined with written words, displaying key terms rather than the full verbatim text is associated with better learning outcomes [14]. For elementary science media, this evidence suggests that a digital pop-up book should pair concise on-page text with narration that elaborates rather than repeats it, and should use animation to clarify processes rather than merely decorate the page.

STEM education offers a pedagogical framework for this purpose. Integrated STEM is commonly understood as teaching the content of two or more STEM disciplines through STEM practices situated in authentic contexts, so that subjects usually taught separately become connected [15]. Here, engineering design gives students a reason to apply scientific knowledge, technology provides tools for investigation, and mathematics allows them to measure and represent what they observe. A meta-analysis of STEM enactments across Asian countries reported a moderate effect on students' learning outcomes ($ES = 0.69$), with the strongest gains in higher-order thinking skills, followed by academic achievement and motivation [16]. The same review found that STEM was most often combined with project-based learning, an approach that has also been shown to reduce misconceptions in science learning [17], and that the teacher remained central to its success. Although teachers value STEM education, they report pedagogical, curricular, and structural barriers, together with concerns about students, assessment, and insufficient support [18], and primary teachers who value STEM rarely enact its practices in class and call for training, equipment, and time [19]. Teachers also struggle to make explicit connections across the STEM disciplines [15]. These difficulties suggest that elementary teachers would benefit from ready-to-use learning materials in which STEM integration is already built into the learning activities.

Despite these promising findings, two limitations in the existing literature deserve attention. The first concerns the pedagogical design of AR media. A systematic review of AR for STEM learning found that most applications offered exploration or simulation activities but rarely assisted students as they carried

out learning tasks, and it called for metacognitive scaffolding and support for inquiry-based activities [10]. Research on AR has also been dominated by media comparison studies: 80% of 92 studies in leading educational technology journals compared AR with another medium, while few examined how and when learning with AR is effective [20]. Pedagogy matters: AR interventions had the greatest impact when they adopted a collaborative pedagogical approach [21], mobile AR integrated with guided inquiry has produced larger gains than guided inquiry alone among Indonesian secondary students [22], and AR used for science learning has been associated with weaker positive learner responses than AR used for languages or social studies, with 3-D visualizations requiring careful design [8]. The second limitation concerns culture. For many students, entering the science classroom is a cultural border crossing between the worldview of their everyday lives and that of school science, and the cognitive conflicts that arise must be resolved through what has been termed collateral learning [23]. Efforts to bridge this gap by integrating indigenous knowledge into science education have largely framed such knowledge as a rich and authentic context for learning scientific content [24], while in Indonesia, compliance-oriented curriculum implementation has been found to marginalize local knowledge and teachers' contextual judgement [25]. Far less attention has been paid to whether a culture's own account of how valid knowledge is obtained could structure the learning process itself.

Catur Pramana offers one such account. The term, meaning "four means of valid knowledge," derives from the Nyāya school of classical Indian philosophy, whose epistemology accepts four *pramāṇas*: perception (*pratyakṣa*), inference (*anumāna*), comparison (*upamāna*), and testimony (*śabda*) [26]. Perception is knowledge gained through direct contact between the senses and an object, and it serves as the foundation for the other three. Inference moves from what is perceived to what is not yet perceived, on the basis of an established relation between a sign and what it indicates, as when fire is inferred from smoke. Comparison yields knowledge of something through its similarity to something already known. Testimony is knowledge received from a reliable source, such as a trustworthy expert or an authoritative text. In classical Nyāya, comparison had a narrow scope, concerned mainly with learning what a word refers to through resemblance [26]; in this study, it is adapted more broadly as the act of comparing objects or results to identify similarities and differences. In Bali, where Hinduism shapes everyday life, Catur Pramana is used as a learning method in formal Hindu schools [27] and has been applied in Hindu religious education to promote student-centred learning [28]. Each *pramāṇa* is a distinct way of justifying a claim, and together they can be aligned with core practices of scientific inquiry: observing phenomena, reasoning from evidence, comparing cases, and consulting reliable sources. Unlike cultural content, this epistemology does not need to be added to a science lesson as context; it can organize the lesson itself.

In this study, the four *pramāṇas* were paired with the four STEM components to structure the learning sequence of the digital pop-up book. *Śabda* was paired with science. Students cannot rediscover all scientific knowledge for themselves; much of it must be learned from reliable sources, and an important aim of science education is to help learners judge which sources deserve their trust [29]. In the book, this role is played by the concept explanations, narration, and animated videos. *Anumāna* was paired with technology. In the accompanying activity sheet, students prepare simple tools and materials, namely a

clear plastic cup, cotton, water, mung bean seeds, a clear plastic sheet, and skewers, a task the sheet also frames as an exercise in responsibility. These tools create a setup in which germination can be followed, and the evidence it produces becomes the basis for inference in the evaluation questions, which ask students to explain why a sprout grows in a particular direction and what might prevent a seedling from growing well. *Upamāna* was paired with engineering. Students construct a mini greenhouse by following illustrated steps in which each stage of the construction is shown as a picture, so that building proceeds by matching one's own work to a visual model. *Pratyakṣa* was paired with mathematics. Over seven days, students observe their seedlings directly and record what they see together with an estimate of seedling height, turning observation into simple quantitative data. AR extends this way of knowing by presenting three-dimensional objects that students can examine from different angles when the real phenomena are too small, too slow, or unavailable in class. Every *pramāṇa* operates across all STEM components; each pairing indicates where a particular way of knowing is foregrounded in the learning sequence.

Indonesia has become one of the most active contributors to research on local wisdom in science education. Publications on local wisdom, sustainability, and education have grown steadily in Scopus-indexed journals, although research collaboration on the theme remains largely local [30]. A recent review of 155 Scopus-indexed articles on integrating local wisdom and STEM in formal science education placed Indonesia second only to the United States in the number of publications [31]. Among the 21 empirical studies reviewed in depth, however, most incorporated indigenous knowledge, cultural practices, local phenomena, or cultural values as content or context for science learning, whereas only one addressed the integration of epistemology and the validation of local knowledge [31]. The same review found that elementary schools were the least represented educational level and that development studies were scarce, with a research-and-development design reported in only one article. Indonesian studies of indigenous science have likewise emphasized its value as a source of relevant contexts, such as the agricultural, medicinal, and household practices of the Baduy community, for teaching scientific concepts [32]. Within this body of work, Catur Pramana itself has been used to structure science learning only rarely. The closest precedent is a set of chemistry learning models for senior secondary students that sequenced the four *pramāṇas* into learning cycles and reported high levels of student activity, achievement, and scientific attitude [33]. That work, however, addressed a single secondary-school subject and did not draw on STEM or immersive technology.

Taken together, these strands of research point to a gap at their intersection. AR-based science media have shown clear potential, but many provide visualization without the pedagogical structure needed to guide students' reasoning [10, 20]. STEM offers such a structure, yet hybrid models linking it with local wisdom are rare [31]. Where culture has been brought into science learning, it has mostly served as content or context, while epistemological integration has received little attention [24, 31]. Existing AR-assisted science books for Indonesian elementary students, meanwhile, have focused on science process skills without drawing on students' cultural ways of knowing [4]. Studies that bring immersive technology, STEM, and a local epistemology together in a single learning medium therefore remain scarce, particularly at the elementary level, and the use of Catur Pramana as a learning structure has so

far been reported mainly in national journals and for secondary chemistry or religious education. The present study addresses this gap by using Catur Pramana not as cultural content to be learned, but as the epistemological structure through which students learn science with an AR-assisted digital pop-up book.

Accordingly, this study aimed to design and develop an AR-assisted digital pop-up book for elementary science that integrates STEM with Catur Pramana, and to evaluate its validity and practicality. The book covers three topics in the elementary science curriculum: plant growth and reproduction, states of matter and their changes, and forces. Following the ADDIE instructional design model, the study addressed three research questions:

RQ1: How can STEM and Catur Pramana be integrated into the design of an AR-assisted digital pop-up book for elementary science?

RQ2: To what extent is the product valid according to content and media experts?

RQ3: How practical was the prototype of the book, prior to the addition of AR features, according to the teachers and students who used it in elementary science classrooms?

2 Methods

2.1 Research design

This study employed design and development research, which Richey and Klein [34] describe as the systematic study of designing, developing, and evaluating instructional programs, processes, and products that must meet criteria of internal consistency and effectiveness. The development process followed the ADDIE model of analysis, design, development, implementation, and evaluation [35]. ADDIE remains one of the most widely used models for designing technology-supported instruction [36], and combining it with prototyping allows a product to be refined on the basis of user feedback before its final validation [37]. Figure 1 presents the research flow, including the activities, success indicators, and outputs of each phase.

A prototype of the book, without AR features, was first trialled with students and teachers in four elementary schools to examine its practicality. Findings from this trial informed revisions that produced the final version, which adopted a unified visual design and added AR features, and the final version was then evaluated by content and media experts. Practicality data therefore refer to the prototype, whereas validity data, including the assessment of the AR features, refer to the final version. Evaluation was formative, and the effect of the final product on learning outcomes is reserved for a subsequent study.

2.2 Participants and setting

Six experts evaluated the final version. Three content experts assessed the accuracy of the science content, its alignment with the curriculum, and the integration of STEM and Catur Pramana, while three

media experts assessed the visual design, the AR features, and the technical functionality of the book. They were selected purposively on the basis of their expertise in elementary science education and in educational media development, respectively, following the common practice of selecting judges according to explicit expertise criteria [38].

The classroom trial of the prototype involved 86 students and 15 teachers from four public elementary schools in Gianyar Regency, Bali, Indonesia, referred to here as Schools A to D. The schools were selected purposively as settings in which Balinese Hindu culture, including the teaching of Catur Pramana, is part of students' everyday lives, and whose school leaders agreed to host the trial. The trial was conducted from July to August 2026 and, across the four schools, covered all three topics of the book. The participating teachers were teachers at the four schools who took part in the trial sessions.

2.3 Development procedure

In the analysis phase, the needs of teachers and students, the elementary science curriculum, the media already in use, and the characteristics of the three topics were examined. In the design phase, the structure and learning sequence of the book were determined, together with the pairing of pramāṇas and STEM components. Each topic was designed to open with concept explanations as a source of reliable knowledge (*śabda*), to continue with an activity sheet in which students prepare tools and materials, construct a simple artefact, and record daily observations, and to close with evaluation questions requiring inference. Audio narration was designed to elaborate on, rather than repeat, the on-page text.

In the development phase, the prototype was built as a digital flipbook in Canva and published online, with activity sheets and quizzes as linked web pages, and the research instruments were prepared. In the implementation phase, the prototype was displayed on a projector screen or interactive flat panel and operated by the teacher, while students followed the presentation and responded in whole-class discussion; students and teachers then completed the practicality questionnaires. In the evaluation phase, the prototype was revised into the final version, which unified the visual design into an open-book pop-up layout accompanied throughout by a mascot in Balinese attire and added AR features that students access by scanning QR codes to view three-dimensional objects. The content and media experts then reviewed the final version and completed the validation sheets independently.

2.4 Instruments

Four instruments were used, all with a five-point rating scale on which higher scores indicate a more favourable assessment. The content validation sheet consisted of ten items in five aspects, and the media validation sheet consisted of ten items in three aspects, as summarized in Table 1.

Table 1
Aspects and indicators of the expert validation sheets

Instrument	Aspect	Items	Indicators
Content	Content and curriculum	3	Alignment with learning objectives; fit with the curriculum structure; logical sequencing
	Language	2	Language suited to students; clear and consistent terms and instructions
	STEM integration	2	Science and technology; engineering design and mathematical patterns
	Catur Pramana elements	2	<i>Pratyakṣa</i> and <i>anumāna</i> ; <i>upamāna</i> and <i>śabda</i>
	Learning effect	1	Engagement and focus
Media	Display and visual design	3	Readability; colours and layout; clarity of images, buttons, and icons
	3-D and AR features	3	Clarity and proportion of 3-D objects; stability of AR objects; animation and audio
	Usability and performance	4	Independent use; navigation; responsiveness; stability without errors

The student practicality questionnaire consisted of eight statements on enjoyment, learning motivation, interest in the display, ease of use, and understanding of the content, together with three negatively worded statements on displeasure, boredom, and difficulty. Reverse-keyed statements are widely used to control for acquiescent responding, although negated statements can be more demanding to process [39]; they were therefore kept short and reverse-scored before analysis. The teacher questionnaire consisted of eight positively worded statements on ease of using the media, ease of delivering the content, attractiveness, suitability for learning, clarity of instructions, efficiency of lesson implementation, usefulness, and overall ease of implementation.

2.5 Data analysis

Content validity was analysed for each item using Aiken's V [40]:

$$V = \frac{\sum s}{n(c-1)}$$

1

$$s = r - l_o$$

2

where r is the score given by a rater, l_o is the lowest possible score (1), c is the number of rating categories (5), and n is the number of raters (3). The overall index for each instrument was the mean of the item-level values, interpreted as high ($V \geq 0.80$), moderate ($0.40 \leq V < 0.80$), or low ($V < 0.40$) [41]. Item-level values were reported in full so that weak items could be identified for revision [38].

Agreement among the experts was estimated using the intraclass correlation coefficient under a two-way random-effects model with absolute agreement [42]. Both ICC(2,1) and ICC(2,k) were calculated and interpreted as poor (< 0.50), moderate ($0.50-0.75$), good ($0.75-0.90$), or excellent (> 0.90) [43]. Because ICC is sensitive to restricted variance among ratings, the percentages of items with identical scores and with scores differing by no more than one point were also reported.

Practicality was calculated for each item and questionnaire as the percentage of the maximum possible score, after the three negatively worded statements had been reverse-scored ($6 - \text{score}$). Percentages were classified into five equal intervals: 81–100% very practical, 61–80% practical, 41–60% moderately practical, 21–40% less practical, and $\leq 20\%$ not practical. Analyses were performed using Microsoft Excel and Python.

2.6 Ethical considerations

The study was conducted with the permission of the principals of the four schools. Written informed consent for students' participation was obtained from their parents, and the schools additionally granted consent as collective guardians of the students during school activities. Teachers and students were informed of the purpose of the trial, and parents were informed that they could withdraw their child from the study at any stage. Completion of the questionnaires was voluntary and anonymous. To protect participants' privacy and anonymity, the schools are referred to by letters only, and the faces of all students in published photographs have been blurred.

3 Results

3.1 Design and development of the book

The analysis identified three topics in the elementary science curriculum suitable for a visual and activity-based treatment: plant growth and reproduction, states of matter and their changes, and forces. The book was designed so that each topic follows the same learning sequence, allowing students to move repeatedly through the four ways of knowing. The pairing of each pramāṇa with a STEM component is summarized in Table 2.

Table 2
Integration of STEM and Catur Pramana in the book

Pramāṇa	STEM component	Part of the book	Example of learning activity
<i>Śabda</i> (testimony)	Science	Concept explanations, narration, and animated videos	Learning the stages of plant growth and the types of natural and artificial plant reproduction
<i>Anumāna</i> (inference)	Technology	Tools and materials of the activity sheet; evaluation questions	Explaining why a sprout grows in a particular direction and what might prevent a seedling from growing well
<i>Upamāna</i> (comparison)	Engineering	Illustrated construction steps	Building a mini greenhouse by matching one's own work to the pictured model at each step
<i>Pratyakṣa</i> (perception)	Mathematics	Daily observation table	Observing seedlings for seven days and recording their condition and estimated height

The final version opens with an information page that introduces the STEM approach and explains the four pramāṇas in language suited to elementary students. Each topic begins with an identity page, followed by concept pages labelled *Science/Sabda Pramana* that combine short on-page text with pop-up illustrations, audio narration, and, for selected content, animated videos, such as a video on the factors affecting plant growth. QR codes on the concept pages display three-dimensional AR objects. The activity sheet, *Making a Seedling House*, guides students through preparing tools and materials (*Technology*), constructing the greenhouse (*Engineering/Upamana*), and observing the seedlings (*Mathematics/Pratyaksa*). The evaluation quiz contains five questions, four requiring written explanations and one asking students to draw the sequence of seed germination. Consistent navigation buttons and a mascot in Balinese attire accompany students throughout. Selected pages are shown in Fig. 2.

During the trial, the teacher presented the prototype on a projector screen or interactive flat panel, while students followed the pages in whole-class discussion (Fig. 3). The prototype contained the same topics and learning sequence as the final version, but it had no AR features and its pages did not share a consistent visual template. Both aspects were addressed in the revision.

3.2 Validity of the final version

Table 3
Aiken's V for each item of the content (C) and media (M) validation sheets

Item	Indicator	V	Category
C1	Alignment with learning objectives	0.92	High
C2	Fit with the curriculum structure	0.58	Moderate
C3	Logical and coherent sequencing	0.75	Moderate
C4	Language suitable for students	0.75	Moderate
C5	Clear and consistent terms and instructions	0.75	Moderate
C6	Facilitation of science and technology	0.75	Moderate
C7	Engineering design and mathematical patterns	0.67	Moderate
C8	Facilitation of <i>pratyakṣa</i> and <i>anumāna</i>	0.75	Moderate
C9	Facilitation of <i>upamāna</i> and <i>śabda</i>	0.75	Moderate
C10	Potential to increase engagement and focus	0.75	Moderate
Content validation overall		0.74	Moderate
M1	Readability of text	0.83	High
M2	Attractiveness of colours and layout	0.83	High
M3	Clarity of images, buttons, and icons	0.75	Moderate
M4	Clarity and proportion of 3-D objects	0.67	Moderate
M5	Stability of AR objects during scanning	0.67	Moderate
M6	Smoothness of animation and audio	0.75	Moderate
M7	Ease of independent use	0.75	Moderate
M8	Functioning navigation	0.75	Moderate
M9	Responsiveness	1.00	High
M10	Stability without errors	0.75	Moderate
Media validation overall		0.78	Moderate

Table 3 shows that both the content and the media validation reached the moderate category overall and that no item fell into the low category. High values were obtained for one content item, concerning alignment with learning objectives, and for three media items, concerning readability, colours and layout, and responsiveness. The lowest values clustered in three areas: fit with the curriculum structure, support for engineering design and mathematical patterns, and the clarity and stability of 3-D and AR objects.

Inter-rater reliability was moderate for the average of the three experts, with ICC(2,k) = 0.71 for content validation and 0.72 for media validation, whereas the single-rater coefficients were poor, with ICC(2,1) = 0.45 and 0.46, respectively. The experts gave identical scores on 70% of the content items and 60% of the media items, their scores never differed by more than one point, and 80% of the 60 ratings were a score of 4. Such concentrated ratings reduce between-item variance and depress ICC values even when raters largely agree.

3.3 Practicality of the prototype

Table 4
Practicality of the prototype according to students and teachers

Respondent	Statement	Mean	%
Students (<i>n</i> = 86)	Enjoyment of using the book	3.99	79.77
	Learning motivation	3.92	78.37
	Interest in the display	3.90	77.91
	Displeasure in using the book ^a	3.16	63.26
	Ease of use	3.94	78.84
	Boredom in learning with the book ^a	3.21	64.19
	Understanding of the content	3.97	79.30
	Difficulty in using the book ^a	3.28	65.58
	Overall		73.40
Teachers (<i>n</i> = 15)	Ease of using the media	3.93	78.67
	Ease of delivering the content	3.80	76.00
	Attractiveness	3.80	76.00
	Suitability for learning	3.73	74.67
	Clarity of instructions	3.93	78.67
	Efficiency of lesson implementation	3.87	77.33
	Usefulness	3.93	78.67
	Overall ease of implementation	4.00	80.00
	Overall		77.50

All values fall in the practical category (61–80%)

^a Negatively worded statement; mean and percentage are reported after reverse scoring

The practicality results refer to the prototype, which did not yet include AR features. Table 4 shows that both students and teachers rated the prototype as practical overall and that every statement fell within the practical category. Among students, the positively worded statements obtained similar and relatively high percentages, whereas the reverse-scored statements on displeasure, boredom, and difficulty obtained noticeably lower ones. Before reverse scoring, the mean ratings on these three statements ranged from 2.72 to 2.84, close to the midpoint of the scale, indicating that students endorsed the positive statements more clearly than they rejected the negative ones. Among teachers, overall ease of implementation obtained the highest percentage and suitability for learning the lowest.

4 Discussion

This study designed an AR-assisted digital pop-up book that integrates STEM with Catur Pramana. The experts judged its final version to be moderately valid, and teachers and students judged its prototype to be practical. Read together, these findings converge on the same strengths and weaknesses even though they come from different respondents and, in part, from different versions of the book.

The first point of convergence concerns visual design. The media experts gave their highest ratings to the readability of text and the attractiveness of colours and layout, and in the trial students rated their interest in the display and their enjoyment of the book among the highest of all statements. Because the experts assessed the final version and the students the prototype, this agreement suggests that visual appeal was already a strength of the prototype, and that the revision, which unified the visual design, built on a feature students already valued.

The second point of convergence concerns fit with the curriculum. The lowest-rated content item was the fit of the book with the curriculum structure, and the lowest-rated teacher statement was the suitability of the book for classroom learning. Two independent groups, judging two versions of the book, thus identified the same aspect as the weakest. A plausible source is visible in the product itself: the cover labels the book as an *IPAS* learning medium, following the integrated science and social studies subject of the current curriculum, whereas its identity pages name the subject as natural science.

The third point of convergence concerns pedagogical depth. Among the STEM items, support for engineering design and mathematical patterns received the lowest rating, and in the trial students rejected statements about boredom and difficulty less decisively than they endorsed the positive statements. Both findings point to the activity-based components, in which students construct and measure, as the least developed parts of the design. This interpretation is tentative, because the teacher-led trial limited students' hands-on engagement with these components. Finally, the AR features, which most distinguish the book from earlier digital pop-up books, received among the lowest media ratings and were absent from the trial, so the component that defines the book's novelty is the one supported by the least evidence.

These patterns become clearer when set against previous research. A recent review found that hybrid models of local wisdom and STEM were rare, that elementary schools were the least represented level,

and that development studies were scarce [31]; the present study addresses all three gaps. It also differs from most Indonesian work on indigenous science, which has drawn on local practices as contexts for learning [24, 32], by using a local epistemology to organize the learning sequence, and it extends the use of Catur Pramana as a learning cycle in senior secondary chemistry [33] to elementary science, integrated STEM, and a digital medium with AR. Compared with an earlier AR science book for Indonesian elementary students, which was framed solely around process skills [4], the present book adds a cultural layer by naming each way of knowing in the students' own tradition, although it has not yet been tested for effects on learning.

The weaknesses identified by the experts mirror those in the wider literature. A systematic review of 117 studies on VR- and AR-supported K-12 STEM learning found that learners frequently faced operational problems with AR, that teachers found it difficult to fit AR activities into the existing curriculum, and that no study addressed engineering [44]. These findings correspond closely to the lowest-rated items in this study and echo the observation that teachers struggle to connect the STEM disciplines [15], a difficulty that appears to persist even when integration is built into a ready-made product. The practicality results are likewise consistent with evidence that animation, music, and sound support young readers [11], which suggests that the narration, animation, and pop-up layout engaged students even without AR. The less decisive rejection of the negative statements may partly reflect how children process negations [39] and the greater inconsistency of younger and lower-achieving respondents on mixed-worded scales [45], but it may also reflect limited opportunities for interaction, since student-centred AR-supported STEM learning has been associated with more positive outcomes than teacher-centred instruction [44].

Beyond these comparisons, the findings offer design-level support for four theoretical perspectives, and they extend one of them. The first is the cognitive theory of multimedia learning. The book was designed so that narration elaborated on, rather than repeated, the on-page text, in line with the modality and redundancy principles [12–14]. Students reported high levels of understanding and enjoyment, and the media experts judged the animation and audio to function adequately. These results do not test the theory, because the study did not compare designs, but they show that its principles can be translated into a culturally situated product that teachers and students find usable.

The second is the view of school science as a cultural border crossing [23]. Most attempts to ease this crossing bring cultural content into the science classroom. In Indonesia, traditional medicines have been used as content within a STEM approach to science teaching [46], and indigenous agricultural, medicinal, and household practices have been identified as contexts for learning science [32]. The present study points to a second route. Instead of importing cultural content, it uses an account of knowledge that students already encounter in their religious and cultural education to name the steps of scientific inquiry. The experts' moderate ratings for the two items on Catur Pramana elements suggest that this route is feasible in a product, although whether it actually eases the border crossing for students remains to be examined. In this sense, the study extends the border-crossing perspective from the level of content to the level of epistemology.

The third is integrated STEM education [15]. The book shows that integration can be organized around epistemic practices, with each STEM component anchored to a way of knowing, rather than only around a shared problem or topic. The weakest STEM item, however, concerned engineering design and mathematical patterns, a result that matches the near absence of engineering in AR-supported K-12 STEM research [44]. This suggests that frameworks for integrated STEM at the elementary level need more concrete design guidance for the engineering component; where engineering design is built into project work, students' grasp of mathematical concepts has improved, provided that teachers receive adequate professional development [47]. The fourth is the view that science literacy includes informed trust in reliable sources [29]. The pairing of *śabda* with science gives this view a culturally familiar form. In the Nyāya tradition, testimony counts as knowledge only when its source is reliable [26], which parallels the expectation that students learn not only to accept scientific knowledge from others but also to judge which sources deserve their trust. This alignment is conceptual, and the present data do not show whether students made such judgements.

Taken together, the findings and their theoretical significance carry implications for developers of learning media, for teachers, and for researchers. For developers, the study shows that a local epistemology can serve as the organizing structure of a science learning medium, not merely as a source of examples, and the approach is in principle transferable to other cultural settings in which a community holds an articulated account of how knowledge is obtained. Two lessons from the weakest-rated aspects should accompany such transfer. First, a culturally grounded product must still align precisely with the formal curriculum. Second, AR features need to be tested for stability across the devices that schools actually use before classroom implementation, since technical and operational problems remain the most common obstacles to AR in K-12 STEM learning [44]. Because Catur Pramana belongs to a living religious tradition, developers should also involve religious educators or community members in reviewing how the concepts are represented.

For teachers, the practicality ratings indicate that the book can serve as a ready-to-use resource in which STEM integration is already built into the learning sequence, which may ease some of the curricular and pedagogical barriers that teachers report when implementing STEM [18]. The trial also shows the limits of teacher-led presentation. To realize the student-centred learning that STEM and AR are meant to support, teachers would need to move from displaying the book at the front of the class toward letting students operate it, scan the AR objects, and carry out the activity sheet in small groups, and schools would need to provide suitable devices. For researchers, particularly those working on ethnoscience in Indonesia, the study suggests a shift in focus from what local culture contributes as content to how local ways of knowing can shape the learning process, in line with calls to examine the epistemological integration of local knowledge [31].

The findings should, however, be interpreted in light of several limitations. The validity and practicality data refer to different versions of the book, so the practicality of the AR features was not examined with users. Students did not operate the book themselves, so their ratings of ease and difficulty reflect how easily they could follow it rather than use it independently. The validation involved three experts per

aspect, several items combined two indicators, and concentrated ratings limited the estimation of inter-rater reliability. The questionnaires were brief self-reports whose mixed wording may have been demanding for young respondents, the needs-analysis findings were not documented in sufficient detail to be reported, learning outcomes were not measured, and the trial was limited to one regency of Bali, where Catur Pramana is part of students' background. Future research should trial the final version with students operating it in small groups, examine its effects on science process skills and conceptual understanding through a quasi-experimental design, observe how students use the four pramāṇas, involve a larger expert panel with single-indicator items, and test the approach with other local epistemologies.

5 Conclusions

This study integrated STEM and Catur Pramana into an AR-assisted digital pop-up book by pairing *śabda* with science in the concept explanations, *anumāna* with technology in the tools and evaluation questions, *upamāna* with engineering in the construction of a mini greenhouse, and *pratyakṣa* with mathematics in daily observation and recording. Content and media experts judged the final version to be moderately valid, rating its alignment with learning objectives and its visual design most favourably, and its fit with the curriculum structure, its engineering and mathematics components, and its 3-D and AR features least favourably. Teachers and students judged the prototype, which did not yet include AR, to be practical.

The main contribution of the study is to show that a local epistemology can serve not only as cultural content but as the structure of the learning process in a science learning medium. Because practicality was established for a prototype without AR and no learning outcomes were measured, the findings support the feasibility of the design rather than its effectiveness. The curriculum alignment, the engineering and mathematics activities, and the AR features should be refined, and the revised book should then be tested with students who operate it themselves.

Declarations

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Author contributions

N.W.S.D.: conceptualization, methodology, investigation, formal analysis, project administration, funding acquisition, writing – original draft. P.B.P.: methodology, investigation, data curation, validation, writing – review and editing. I.M.A.S.: software, resources, visualization, writing – review and editing. All authors read and approved the final manuscript.

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Data availability

The data generated and analysed during the current study are available from the corresponding author on reasonable request.

Ethics approval and consent to participate

Ethical approval for this study was granted by the Institute for Research and Community Service (LPPM), Universitas Markandeya (approval No. 052/LPPM/UMark/VI/2026). The study was conducted with the permission of the principals of the four participating schools. Written informed consent for the students' participation was obtained from their parents, and the schools additionally granted consent as collective guardians of the students during school activities. Parents were informed that they could withdraw their child from the study at any stage. Participation of teachers was voluntary, and all questionnaires were completed anonymously.

Consent for publication

Not applicable. The photographs in Fig. 3 contain no identifiable images of individuals; the faces of all participants and the school name have been blurred.

Competing interests

The authors declare no competing interests.

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Figures

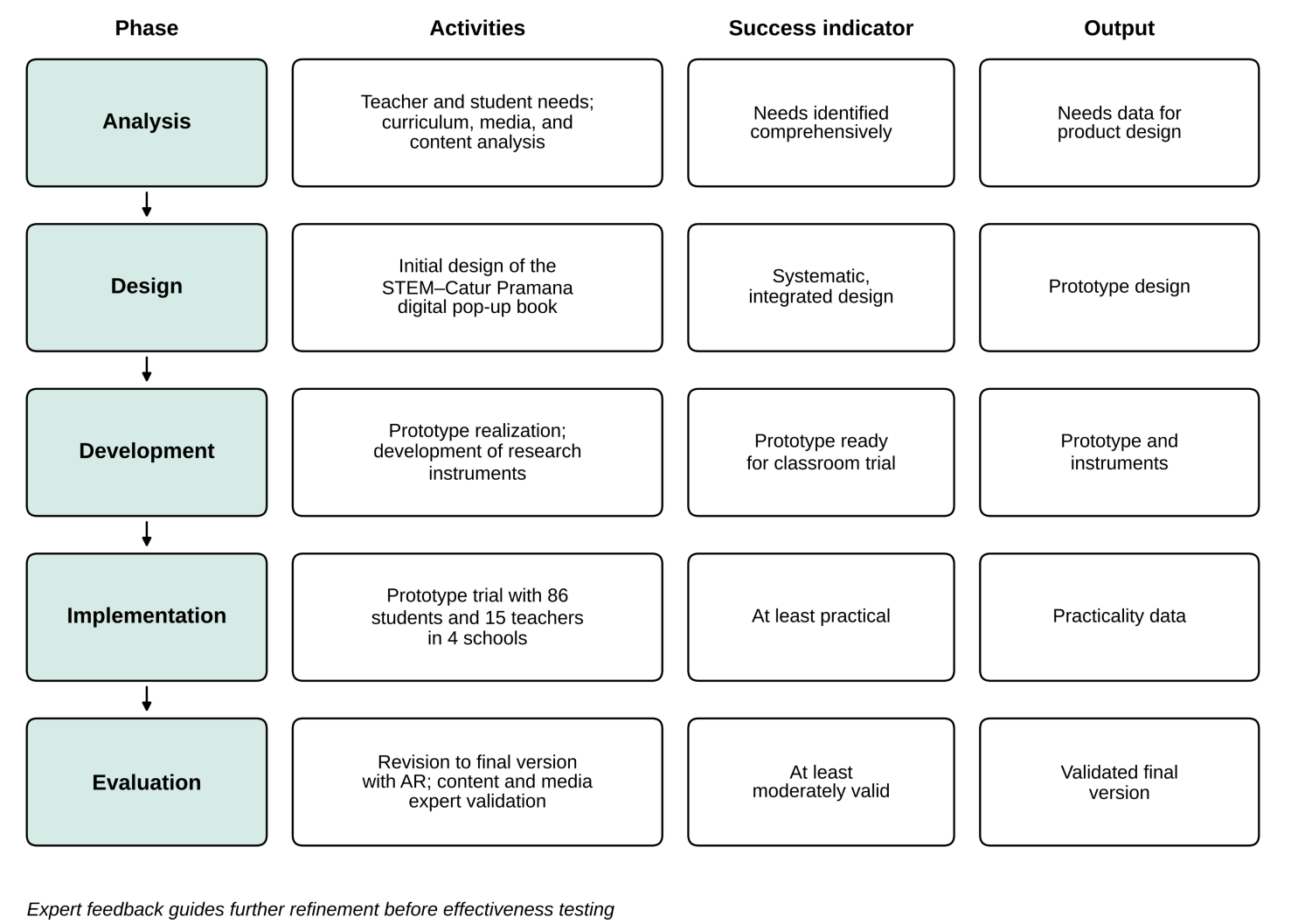


Figure 1

Research flow based on the ADDIE model, showing the activities, success indicators, and outputs of each phase



Figure 2

Selected pages of the final version: **a** information page on STEM and Catur Pramana, **b** concept page with pop-up layout, **c** activity sheet, and **d** evaluation quiz. Page content is in Indonesian, the language of instruction



Figure 3

Classroom trial of the prototype: **a** a teacher presenting the topic of plant growth, and **b** students following the topic of changes in states of matter. Faces and identifying information have been blurred