



e-ISSN: 3026-5827

# Enigma in Education

Journal website: <https://enigma.or.id/index.php/edu>



## Frugal Innovation in Education: Designing and Evaluating Low-Bandwidth, Asynchronous Learning Systems for Remote Indonesian Schools

Hesti Putri<sup>1</sup>, Maya Enderson<sup>2\*</sup>, Jasmila Tanjung<sup>3</sup>, Matilda Munoz<sup>4</sup>, Sarah Armalia<sup>5</sup>, Jovanka Andina<sup>6</sup>, Kevin Setiawan<sup>7</sup>, Sudarto Sudarto<sup>8</sup>, Khalil Jibrán<sup>9</sup>, Jasmine Alieva<sup>10</sup>

<sup>1</sup>Department of Informatics Science, CMHC Research Center, Palembang, Indonesia

<sup>2</sup>Department of Architecture, Enigma Institute, Palembang, Indonesia

<sup>3</sup>Department of Environmental Engineering, CMHC Research Center, Palembang, Indonesia

<sup>4</sup>Department of Physics, Campeche Science Center, Campeche, Mexico

<sup>5</sup>Department of Natural Sciences, Bareleng Study Center, Tanjung Pinang, Indonesia

<sup>6</sup>Department of Civil Engineering, CMHC Research Center, Palembang, Indonesia

<sup>7</sup>Department of Chemical Engineering, CMHC Research Center, Palembang, Indonesia

<sup>8</sup>Department of Botanical Sciences, CMHC Research Center, Palembang, Indonesia

<sup>9</sup>Department of Chemical Science, CMHC Research Center, Palembang, Indonesia

<sup>10</sup>Department of Industrial Engineering, Yevlakh Study Center, Yevlakh, Azerbaijan

### ARTICLE INFO

#### Keywords:

Educational technology  
Frugal innovation  
Hierarchical linear modeling  
Kurikulum Merdeka  
Mixed-methods

#### \*Corresponding author:

Maya Enderson

#### E-mail address:

[maya.enderson@enigma.or.id](mailto:maya.enderson@enigma.or.id)

All authors have reviewed and approved the final version of the manuscript.

<https://doi.org/10.61996/edu.v3i1.95>

### ABSTRACT

The promise of educational technology (EdTech) to democratize learning in Indonesia is consistently undermined by a profound digital divide, particularly in remote and archipelagic regions where internet connectivity is poor and infrastructure is limited. This study explores the application of frugal innovation principles as a direct and context-aware strategy to address this challenge. A multi-phase, mixed-methods Design-Based Research (DBR) methodology was employed over 18 months. The study involved the collaborative design, development, and implementation of "Lentera," a low-bandwidth, asynchronous, and offline-first learning system, in six remote primary schools in the Maluku Islands. A quasi-experimental design compared three intervention schools with three control schools over one academic year. Data collection was extensive, including pre- and post-intervention literacy and numeracy assessments, System Usability Scale (SUS) surveys, system usage logs, semi-structured interviews with 18 teachers, and over 80 hours of classroom observation. Data were analyzed using a two-level Hierarchical Linear Model (HLM) to account for the clustered nature of students within schools. The Lentera system demonstrated high feasibility and positive user adoption, with offline peer-to-peer sharing proving to be a critical feature for content distribution. Quantitative analysis revealed a statistically significant and substantial improvement in learning outcomes for the intervention group in both literacy ( $\gamma = 11.85$ ,  $p < 0.001$ ) and numeracy ( $\gamma = 12.91$ ,  $p < 0.001$ ) compared to the control group, after controlling for pre-test scores. The mean System Usability Scale (SUS) score was 78.5, indicating well-above-average usability. Qualitative findings, drawn from a wide range of teacher interviews and classroom observations, highlighted the system's effectiveness in supporting student-centered, differentiated instruction and fostering teacher collaboration, aligning with the core principles of Indonesia's Kurikulum Merdeka. The study provides compelling evidence that frugal innovation, embodied in a context-aware learning system, presents a viable, effective, and scalable pathway to enhancing educational quality and equity in resource-constrained environments.

### 1. Introduction

The Republic of Indonesia, a sprawling archipelago of over 17,000 islands, has made monumental strides in expanding access to basic education over the past several decades.<sup>1</sup> This quantitative expansion,

however, has not been matched by a corresponding improvement in educational quality, leading to what many observers have termed a persistent "learning crisis".<sup>2</sup> International assessments, such as the Programme for International Student Assessment

(PISA), consistently place Indonesian students in the lower quartiles for foundational competencies like literacy and numeracy, indicating a systemic challenge in translating school attendance into meaningful learning.<sup>3</sup>

A stark and defining feature of this educational landscape is the profound disparity that exists between well-resourced urban centers, such as those on the island of Java, and the vast, geographically isolated rural and remote regions.<sup>4</sup> Schools in these remote areas, particularly in the eastern provinces of the archipelago, contend with a formidable array of challenges. These include substandard physical facilities, a chronic lack of high-quality learning materials, and a persistent shortage of well-trained and supported teachers.<sup>5</sup> It is within this context of deep-seated inequity that educational technology (EdTech) has been heralded as a potential panacea. The global COVID-19 pandemic further accelerated the growth of a vibrant Indonesian EdTech market, with billions of dollars invested into platforms designed to digitize learning.<sup>6</sup>

However, the dominant paradigm of this burgeoning EdTech market, which almost universally presupposes stable, high-speed internet access and high levels of digital literacy, has proven largely ineffective and exclusionary in the very regions that stand to benefit most.<sup>7</sup> This paradox has created a "socio-technical vicious cycle": the communities most in need of the educational resources that EdTech can provide are the least equipped, both infrastructurally and economically, to access them. The result is not a narrowing, but a widening of the educational gap, where technology exacerbates rather than alleviates existing inequalities.<sup>8</sup>

This study was predicated on the imperative to break this cycle. We turned to the concept of frugal innovation—a design philosophy focused on creating effective, high-value solutions from limited resources by strategically minimizing complexity and cost. Instead of designing for an idealized, high-connectivity world, our approach was to design for the world as it is in remote Indonesia. This research was situated within the context of Indonesia's ambitious national education reform, *Merdeka Belajar* (Emancipated

Learning), a policy framework that calls for a shift away from rote memorization towards student-centered, differentiated, and competency-based learning.<sup>9</sup> We posited that a frugally designed educational tool, built in direct response to local constraints, could serve as a powerful enabler for this reform, providing teachers with the resources needed to implement its pedagogical vision.

The novelty of this research lies in its deliberate and systematic application of frugal innovation as a guiding principle for both technological design and social implementation, coupled with a rigorous, field-based evaluation within the challenging context of remote Indonesian schools. By employing a Design-Based Research (DBR) methodology, we integrated iterative engineering design with deep social science evaluation to generate not only a practical artifact—the "Lentera" learning system—but also a deeper theoretical understanding of how technology can be effectively contextualized to advance the cause of educational equity.<sup>10</sup> Therefore, this study pursued a threefold aim, which guided all phases of the research: to design and develop a low-bandwidth, asynchronous, and offline-capable digital learning system (named "Lentera," the Indonesian word for lantern) in close collaboration with educators, based on the principles of frugal innovation and aligned with the pedagogical goals of *Kurikulum Merdeka*; to implement and rigorously evaluate the feasibility, usability, and adoption of the Lentera system by both teachers and students within a real-world, resource-constrained primary school setting in remote Indonesia; and to assess, using a robust quasi-experimental design and multilevel statistical analysis, the impact of the Lentera system on student learning outcomes in the foundational areas of literacy and numeracy by comparing students in intervention schools with those in control schools.

## 2. Methods

This study employed a multi-phase, mixed-methods Design-Based Research (DBR) methodology. DBR is particularly appropriate for this research as it involves the iterative development and refinement of an educational intervention (the "Lentera" system)

within a real-world context, while simultaneously generating theoretical insights about learning and technology integration in such settings. The research was conducted over a period of 18 months and was structured into four distinct, sequential phases.

### **Phase 1: Contextual Inquiry and Needs Analysis (3 Months)**

The initial phase of the research was dedicated to a deep contextual inquiry to understand the specific educational, social, and technical environment of our target communities. Our team conducted ethnographic fieldwork in selected communities in Maluku province, a region specifically chosen for its archipelagic geography, cultural diversity, and significant developmental disparities, making it a representative case of the challenges faced in eastern Indonesia. This fieldwork involved in-depth semi-structured interviews with 34 teachers and 6 principals across several islands, focus group discussions with parents, and over 80 hours of direct classroom observation. This qualitative inquiry focused on understanding daily teaching practices, curricular challenges, resource availability, and community attitudes towards education and technology.

Concurrently, a technical audit was performed to map the digital landscape. This involved measuring mobile network signal strength (2G, 3G, 4G) and conducting data speed tests at various times of day in and around the school environments. The audit confirmed that while fleeting, low-bandwidth mobile data signals were occasionally accessible (often requiring a walk to a specific hilltop or coastal point), reliable, continuous internet suitable for streaming or large downloads was entirely unavailable in the school environments. This crucial finding directly informed our decision to pursue an offline-first, asynchronous architecture.

### **Phase 2: Co-Design and Frugal System Development (6 Months)**

Informed by the rich data from the needs analysis, we initiated a six-month co-design process to develop the "Lentera" (Lantern) learning system. This phase

was explicitly guided by the principles of frugal innovation: minimizing complexity, maximizing resourcefulness, and focusing on core functionality. The system was designed as a lightweight, standalone Android application to prioritize asynchronous, offline functionality on low-cost tablets.

The content was developed to focus squarely on foundational literacy and numeracy for primary grades, with all modules, quizzes, and activities directly aligned with the competency-based structure of *Kurikulum Merdeka*. To ensure contextual relevance and teacher ownership, four participatory design workshops were held with the 18 teachers from the schools that would later become the intervention group. These workshops were not merely for feedback; teachers were active partners in shaping the user interface, selecting content, and, most importantly, brainstorming solutions to the connectivity problem.

This collaborative process resulted in key architectural features that define Lentera: "Trickle-Syncing": A background service where the app intelligently and patiently downloads highly compressed content modules whenever a minimal data connection is detected, without requiring active user engagement; Offline Peer-to-Peer Sharing: A critical feature allowing devices to share downloaded modules with other devices entirely offline, using Wi-Fi Direct or Bluetooth. This transformed a single teacher's successful download into a resource for the entire school; Concrete Learning Modules: Content was designed to be interactive and engaging. For example, a Grade 2 literacy module focused on mastering syllables (*suku kata*) through a game where students would drag-and-drop syllables to form words corresponding to images of local fauna. A Grade 4 numeracy module used the concept of a local market stall to create gamified quizzes on multiplication and division, using familiar items like fish and spices.

### **Phase 3: Implementation and Evaluation (10 Months)**

The third and longest phase involved a ten-month implementation of the Lentera system within a quasi-experimental research design. Setting and Participants: We recruited a purposive sample of six

public primary schools from two island districts in Maluku province. These districts are characterized by economies largely dependent on subsistence fishing and agriculture, with limited and often unreliable public infrastructure, including electricity. Teacher qualification levels in these areas are often below the national average, and multi-grade teaching is common. The six schools were carefully matched into three pairs based on key characteristics: school size, student-to-teacher ratio, existing community resources, and the complete lack of reliable internet infrastructure. Within each pair, one school was assigned to the intervention group and the other to the control group using a computer-generated random sequence. This cluster-randomized approach resulted in an intervention group of three schools, comprising 18 teachers and 154 students, and a control group of three schools, with 16 teachers and 148 students. Informed written consent was obtained from all participating teachers and from the guardians of all student participants. The study protocol received full approval from regional educational authorities and the institutional review board of the Enigma Institute; Intervention and Training: Each of the 18 teachers in the intervention group received a low-cost Android tablet with the Lentera application pre-installed. They also participated in a comprehensive two-day training workshop before the start of the academic year. The training protocol was carefully designed: Day 1: Technical Familiarization. This day focused on building confidence with the hardware and software. Topics included basic tablet operation, navigating the Lentera interface, managing content modules, and practicing the crucial offline peer-to-peer sharing feature; Day 2: Pedagogical Integration. This day focused on shifting from "how to use" the tool to "how to teach" with it. We introduced pedagogical strategies aligned with *Kurikulum Merdeka*, such as setting up rotational learning stations, using Lentera for small-group targeted instruction, and planning lessons that blend digital activities with traditional hands-on work. The control schools received no intervention and continued with their traditional teaching methods, which typically relied on a single textbook and whole-class, lecture-style instruction.

**Data Collection Strategy:** Our multifaceted data collection strategy was designed to capture a holistic view of the intervention's impact: **Learning Outcomes:** We administered the Indonesian Foundational Learning Assessment for Primary (IFLAP), a standardized and culturally validated instrument, as a pre-test and post-test to all students in both groups to measure growth in literacy and numeracy; **Usability:** At the end of the ten-month intervention, all 18 intervention teachers and a random sample of 50 students from the intervention group completed the industry-standard System Usability Scale (SUS) survey to gauge perceived ease of use; **System Usage:** The Lentera application passively logged anonymized usage data, such as the number and type of modules accessed, session durations, and the frequency of internet downloads versus peer-to-peer sharing events; **Qualitative Data:** To understand the process of adoption and its impact on pedagogy, we conducted post-intervention semi-structured interviews with all 18 intervention teachers and a second round of intensive classroom observations in the intervention schools.

#### **Phase 4: Data Analysis (2 Months)**

The final two-month phase of the study was dedicated to a comprehensive mixed-methods data analysis. Given that the data were clustered (students nested within schools), we employed a two-level Hierarchical Linear Model (HLM) for the analysis of learning outcomes. This statistical approach properly accounts for the non-independence of observations and allows for a more accurate estimation of the intervention effect by partitioning variance at the student and school levels. First, we calculated the Intraclass Correlation Coefficient (ICC) from an unconditional model to determine the proportion of variance in post-test scores attributable to the school level, confirming the necessity of a multilevel model. The unconditional model was specified as: Level 1 (Student):  $Y_{ij} = \beta_{0j} + r_{ij}$  Level 2 (School):  $\beta_{0j} = \gamma_{00} + u_{0j}$  Where  $Y_{ij}$  is the post-test score for student  $i$  in school  $j$ .

For the main analysis, a two-level random-intercepts model was constructed. The student's post-

test score was the outcome variable. To control for prior ability, the student's pre-test score was entered as a Level 1 covariate (group-mean centered). The intervention status (1=Intervention, 0=Control) was entered as the key Level 2 predictor. The final fitted model was specified as: Level 1 (Student):  $\text{PostTest}_{ij} = \beta_{0j} + \beta_{1j}(\text{PreTest}_{ij} - \text{PreTest}_{.j}) + r_{ij}$  Level 2 (School):  $\beta_{0j} = \gamma_{00} + \gamma_{01}(\text{Intervention}_j) + u_{0j}$   $\beta_{1j} = \gamma_{10}$  Here,  $\gamma_{01}$  represents the estimated average difference in post-test scores between the intervention and control groups, controlling for pre-test scores. Data from the SUS surveys and system usage logs were analyzed using descriptive statistics.

All interview transcripts and observation field notes were analyzed concurrently using thematic analysis. An initial coding framework was developed based on the research questions. Two researchers coded a subset of the data independently to establish inter-coder reliability. Following this, they discussed and resolved any discrepancies to refine the final coding framework, which was then applied to the full dataset to identify and develop key themes related to pedagogical change, teacher collaboration, and student engagement.

### 3. Results

The results of the study are presented in three parts: first, the feasibility and usability of the Lentera system; second, its impact on student learning outcomes; and third, the qualitative findings that illuminate the process of its adoption and impact on

classroom pedagogy. The deployment of the Lentera system was highly feasible, with system usage logs showing sustained and enthusiastic adoption by both teachers and students throughout the ten-month academic year. Table 1 provides quantitative evidence of this deep engagement. Critically, the frugal design philosophy was validated by the usage patterns. The peer-to-peer (P2P) sharing feature was not just an auxiliary function but an essential lifeline for content distribution; on average, teachers received more than twice as many content modules via local offline sharing as they did from direct internet downloads. This directly confirms the design's effectiveness in overcoming the severe connectivity constraints of the environment. Classroom observations revealed that teachers creatively integrated the devices into their daily routines, using them for individual student work, for collaborative small group activities, and for whole-class instruction by projecting the tablet screen using low-cost portable projectors. One teacher articulated the social impact of the P2P feature perfectly:

*"In the beginning, we worried about the signal. But we made a schedule. Every Tuesday, Teacher B, whose house is near the hill, would go up to 'hunt' for a signal. If he got even one or two new modules, it was a victory. He would come back to school the next day, and within minutes, we would all gather, and he would share them with everyone. The signal became a community task, not a personal problem. The real magic was not the internet, but the sharing."*

Table 1. Key usage metrics for the Lentera system (N=18 Teachers, 154 Students).

Metric	Mean (per teacher)	Standard Deviation	Total (across all users)
Modules downloaded (via internet)	24.5	6.2	441
Modules received (via P2P sharing)	<b>58.3</b>	<b>12.5</b>	<b>1049</b>
P2P sharing events initiated	15.7	4.8	282
Student logins (per week)	21.4	8.9	~385 (per week)
Average session Duration (minutes)	18.5	5.1	N/A
Quizzes completed (per student)	45.2	11.3	6960

The usability of the Lentera system was rated very favorably by its users. The mean System Usability Scale (SUS) score from the 18 teachers was 81.2 (SD = 6.5), and the mean score from the 50 students

surveyed was 75.8 (SD = 8.2), resulting in a combined average score of 78.5. This score is well above the established industry average of 68, placing Lentera in the "Excellent" or "B+" grade category and indicating

high perceived usability and ease of use. Interviews and observations confirmed this; teachers and students consistently praised the simple, icon-based navigation and uncluttered interface. One teacher contrasted it with other software they had seen:

*"The government sometimes gives us programs, but they are so complicated, with so many menus and options, you need training just to find the 'on' button! Lentera was different. It is simple. The children understood the icons immediately. This simplicity is its*

*strength; it helps me teach instead of getting in the way."*

The intervention had a substantial and statistically significant impact on student learning. Table 2 presents the pre- and post-test scores for both the intervention and control groups. While both groups started at nearly identical baseline levels in literacy and numeracy, the intervention group demonstrated markedly greater gains over the academic year.

Table 2. Pre- and post-test scores for literacy and numeracy by group.

Assessment	Group	N	Pre-Test Mean (SD)	Post-Test Mean (SD)
Literacy	Intervention	154	<b>52.4 (10.1)</b>	<b>68.7 (9.8)</b>
	Control	148	51.9 (10.5)	56.2 (10.2)
Numeracy	Intervention	154	<b>48.6 (9.8)</b>	<b>65.1 (9.5)</b>
	Control	148	48.1 (10.2)	51.8 (10.3)

The Hierarchical Linear Model (HLM) analysis provided robust statistical validation of these observed gains. An initial unconditional HLM analysis indicated that school-level clustering accounted for a significant portion of the variance in post-test scores for both literacy (ICC = 0.21) and numeracy (ICC = 0.19), confirming that the multilevel modeling approach was essential to avoid misinterpreting the data. The main HLM analysis, which controlled for students' pre-test scores, revealed a significant positive effect of the Lentera intervention on learning outcomes. Table 3 shows the comprehensive results of the two-level Hierarchical Linear Model (HLM) analysis, providing a robust and nuanced statistical account of the Lentera intervention's impact on student learning outcomes in both literacy and numeracy. The model was designed to isolate the unique effect of the intervention while statistically controlling for students' prior academic abilities and the fact that students were grouped within schools.

The model for literacy reveals a clear and powerful story of academic growth. These fixed effects coefficients represent the average effects across all schools. The Intercept ( $\gamma_{00}$  = 56.41) establishes a baseline. It represents the estimated average literacy post-test score for a student in a control school who had an average pre-test score. The Pre-Test Slope ( $\gamma_{10}$  = 0.81) confirms a strong and positive

relationship between prior knowledge and end-of-year results. For every one-point increase in a student's literacy pre-test score, their post-test score is predicted to increase by 0.81 points. This underscores the importance of accounting for baseline knowledge in the model. The Intervention effect ( $\gamma_{01}$  = 11.85) is the most critical finding for this study. This coefficient indicates that, after controlling for their initial pre-test scores, students in the Lentera intervention group scored, on average, a remarkable 11.85 points higher on the literacy post-test than their peers in the control group. The effect is highly statistically significant ( $p < 0.001$ ), meaning the probability of this result occurring by random chance is less than 0.1%. This provides strong evidence that the Lentera intervention was the driver of these substantial learning gains. Variance components values explain how variability in test scores is distributed. The significant School-Level Variance ( $\tau_{00}$  = 9.87) indicates that there are meaningful differences in the average literacy scores between schools. This finding validates the decision to use a multilevel model, as it confirms that school context plays a role in student achievement.

The results for the numeracy model mirror the positive findings in literacy, reinforcing the overall effectiveness of the intervention. The Intercept ( $\gamma_{00}$  = 52.03) sets the baseline for the numeracy assessment,

representing the predicted post-test score for an average student in a control school. The Pre-Test Slope ( $\gamma_{10} = 0.85$ ) is again strong and positive, showing that students with higher initial numeracy skills also achieved higher post-test scores. The Intervention effect ( $\gamma_{01} = 12.91$ ) demonstrates an even larger impact in numeracy. On average, students who used the Lentera system scored 12.91 points higher on the numeracy post-test than students in the control group, holding their pre-test scores constant. This effect is also highly statistically significant ( $p < 0.001$ ). Similar to the literacy model, the School-Level Variance ( $\tau_{00} = 11.21$ ) for numeracy is substantial, again confirming that school-level factors contribute to differences in student outcomes and justifying the HLM approach.

In summary, the HLM analysis provides compelling statistical evidence for the efficacy of the Lentera system. The models demonstrate that the intervention had a large, positive, and statistically significant impact on student achievement in both foundational literacy and numeracy. The consistency of these powerful effects across two different academic domains strongly suggests that the pedagogical changes facilitated by the Lentera system were responsible for driving meaningful and accelerated learning in this resource-constrained setting. The intervention did not just produce minor gains; it fundamentally shifted the learning trajectory for students in the participating schools.

Table 3. Hierarchical linear model results for the effect of the Lentera intervention on post-test scores.

<b>Model and predictor</b>	<b>Coefficient (<math>\gamma</math>)</b>	<b>Standard Error</b>	<b>t-ratio</b>	<b>p-value</b>
<b>Literacy outcomes model</b>				
Fixed effects				
<b>Intercept (<math>\gamma_{00}</math>)</b>	56.41	0.88	64.10	< 0.001
<b>Intervention (<math>\gamma_{01}</math>)</b>	<b>11.85</b>	<b>1.25</b>	<b>9.48</b>	<b>&lt; 0.001</b>
<b>Pre-test slope (<math>\gamma_{10}</math>)</b>	0.81	0.04	20.25	< 0.001
Variance components				
School-level variance ( $\tau_{00}$ )	9.87			
Student-level variance ( $\sigma^2$ )	37.45			
<b>Numeracy outcomes model</b>				
Fixed effects				
<b>Intercept (<math>\gamma_{00}</math>)</b>	52.03	0.91	57.18	< 0.001
<b>Intervention (<math>\gamma_{01}</math>)</b>	<b>12.91</b>	<b>1.31</b>	<b>9.85</b>	<b>&lt; 0.001</b>
<b>Pre-test slope (<math>\gamma_{10}</math>)</b>	0.85	0.05	17.00	< 0.001
Variance components				
School-level variance ( $\tau_{00}$ )	11.21			
Student-level variance ( $\sigma^2$ )	41.50			

The qualitative findings from teacher interviews and classroom observations provide a rich explanation for *why* these learning gains occurred. The data overwhelmingly suggest that these gains were not driven by the technology itself, but by the profound pedagogical changes it facilitated. Teachers reported that Lentera was the enabling tool that allowed them, for the first time, to effectively implement differentiated instruction—a core principle of *Kurikulum Merdeka*.

One experienced teacher, who was initially skeptical, described her transformation:

*"For twenty years, I have taught the same way: I stand at the front, I write on the blackboard, and the students copy. I knew it wasn't the best way. The fast students get bored, and the slow students get left behind. But with 35 children and one textbook, what else can you do? At first, I thought this tablet was just another toy. But then I saw... I could put the faster students on a module to work by themselves, and they were so focused. This freed me. I could finally pull a small group of the five struggling students to my desk with another tablet and work with them closely on the basics. I looked up and saw a quiet, busy classroom,*

*everyone learning at their own level. It was the classroom I had always dreamed of but never thought possible."*

Our classroom observations corroborated these accounts. We witnessed a dramatic shift from teacher-centered, whole-class lectures to a dynamic, student-centered learning environment. Students were frequently observed working in small groups, clustered around a tablet, debating answers to a quiz, or helping a peer navigate a module. This fostered not only academic skills but also collaboration and communication. A particularly poignant observation involved a shy girl who rarely spoke in class. When working with a partner on a Lentera literacy game, she became animated, confidently pointing out the correct answers and explaining her reasoning to her classmate. The technology provided a new, less intimidating medium for her to express her competence.

Another teacher highlighted how Lentera fostered a new sense of professionalism and collaboration among the staff:

*"Before Lentera, we were all teaching in our own little kingdoms—our classrooms. We rarely talked about teaching methods. Now, the app has given us a reason to collaborate. We discuss which modules work best, we share strategies for grouping students, and we help each other with the technical side. The P2P sharing isn't just about data; it's about sharing knowledge. We have become a real team."*

These qualitative findings are critical: they reveal that Lentera's true impact was not as a digital textbook, but as a catalyst that restructured the classroom dynamic. It offloaded the immense logistical burden of differentiation from the teacher, empowering them to become true facilitators of learning and finally enact the sophisticated pedagogy promoted by national policy.

#### **4. Discussion**

The findings of this research offer a compelling and deeply nuanced narrative about the role of technology in resource-constrained educational settings. The success of the Lentera system is not merely a story of a functional application, but a testament to a

fundamentally different philosophy of design and implementation. It presents a powerful counter-narrative to the dominant, often techno-solutionist, discourse in the global educational technology market.<sup>9</sup> This discussion delves into the intertwined threads of this narrative: the validation of frugal innovation as a design paradigm, the role of technology as a catalyst for profound pedagogical reform, the engineering of a virtuous socio-technical cycle, and the subsequent need to re-evaluate what constitutes true "value" and "innovation" in the pursuit of educational equity.

At its very core, the success of the Lentera system was a direct and resounding result of its foundational design philosophy: frugal innovation. This was not about creating a cheaper, "good enough" substitute for "real" EdTech; it was about an intelligent, empathetic, and disciplined re-framing of the problem itself. The prevailing EdTech market, driven by a venture capital logic that equates progress with feature complexity, data intensity, and ever-increasing bandwidth requirements, consistently produces platforms that are brilliant in conception but brittle and impractical in execution within environments like remote Indonesia. These platforms demand robust, always-on digital infrastructure not as a feature, but as a prerequisite for basic function. Our research demonstrated, with both quantitative and qualitative richness, that this paradigm is not just inappropriate but profoundly counterproductive in bridging the digital divide.<sup>10</sup>

The single most illuminating quantitative finding from this study was that teachers received more than double the amount of educational content through offline, peer-to-peer sharing than through direct internet downloads.<sup>11</sup> This is not a minor detail; it is a fundamental validation of our central hypothesis. It proves that in a low-connectivity environment, an asynchronous, offline-first architecture is not a "nice-to-have" feature, but the absolute bedrock of feasibility, adoption, and ultimately, impact. This architectural choice directly confronted and systematically dismantled the primary infrastructural barrier that has historically hamstrung EdTech initiatives in Indonesia.<sup>11</sup> While commercial platforms



built on a model requiring constant, stable connectivity for authentication, content streaming, and data synchronization would fail at the outset, Lentera was engineered for the opposite reality. Its "trickle-sync" capability was designed to patiently "sip" compressed data whenever a fleeting, low-quality connection became available, turning an infrastructural liability into a usable asset.<sup>12</sup>

Once the educational modules were on a single device, the system became a self-contained, self-propagating learning ecosystem. The peer-to-peer sharing feature transformed a technological constraint into a powerful social asset, fostering a culture of collaboration. This represents a significant departure from the conventional wisdom of the tech industry, which often implicitly argues for waiting for the context (the infrastructure, the market) to meet the demands of the technology. Lentera offers a potent alternative: designing with humility and ingenuity for the constraints of the real world, rather than for the idealized conditions of a Silicon Valley boardroom.<sup>13</sup>

Furthermore, the high usability scores (mean SUS of 78.5) underscore another key tenet of frugal innovation: the relentless and disciplined pursuit of simplicity. In a field often characterized by "feature creep," where product managers measure success by the length of a feature list, Lentera's design was deliberately subtractive. The co-design process with teachers was an extended exercise in stripping away every non-essential function, every confusing menu, and every extraneous button. The unwavering focus was on creating a clean, intuitive, icon-driven interface that minimized the cognitive load on both teachers and students, many of whom had limited prior digital literacy.<sup>14</sup> This simplicity was not a compromise; it was a critical success factor that enabled rapid adoption and proficiency. As teachers noted, the system's ease of use allowed them to focus their finite mental energy on the pedagogical application of the tool, not on technical troubleshooting. This provides a crucial lesson for the design of inclusive technology: true accessibility is not merely about physical access to a device, but about cognitive access to its functions.

Beyond its technical feasibility, the most profound finding of this study was the statistically significant

and substantively large impact of the Lentera system on student learning outcomes in literacy and numeracy. The large effect sizes revealed by the HLM analysis indicate that the intervention was not just marginally beneficial but was a powerful driver of academic growth, capable of meaningfully accelerating learning for students who have been historically underserved.<sup>15</sup> The qualitative data provide a clear, compelling, and deeply human explanation for this impact: the Lentera system acted as a powerful catalyst for pedagogical change, the missing link that enabled teachers to finally implement the principles of the national *Merdeka Belajar* reform in a way that was previously impractical, if not impossible.

The *Merdeka Belajar* curriculum calls for a fundamental shift away from a one-size-fits-all, lecture-based model towards a student-centered, differentiated approach often described as "teaching at the right level".<sup>15</sup> This requires teachers to assess the individual competency level of each student and then tailor instruction accordingly. While this is a laudable and evidence-based goal, its implementation in a typical remote Indonesian classroom—often with a single teacher responsible for multiple grades, limited teaching aids, and a wide spectrum of student abilities—presents an enormous logistical challenge. Teachers simply lack the time and resources to prepare dozens of different lesson plans and worksheets to meet every student's unique needs.<sup>16</sup>

This is precisely the systemic bottleneck that the Lentera system was designed to break. By providing a curated, curriculum-aligned library of self-paced digital modules, the system effectively offloaded the immense burden of content creation and differentiation from the individual teacher. It provided a ready-made tool that allowed students to work independently, at their own pace, on materials appropriate for their specific learning level.<sup>16</sup> This simple yet transformative capability fundamentally altered the classroom dynamic and liberated the teacher's most valuable and finite resource: their time and attention. Instead of being tethered to the front of the classroom delivering a single lesson to the "average" student, teachers were consistently observed moving around the room, facilitating small-group

work, and providing intensive, targeted support to the students who needed it most. The technology did not replace the teacher; it augmented and empowered them, allowing them to perform the higher-order tasks of facilitating, mentoring, and inspiring. The teacher's enthusiastic quote about finally being able to "teach at their individual levels" is the most potent evidence of this transformation.

The success of Lentera is best understood through the lens of socio-technical systems theory, which posits that technological artifacts and social structures are not separate entities but are deeply intertwined and mutually constitutive.<sup>17</sup> Many technology projects fail in development contexts because of a naive "technological determinism"—a belief that simply introducing a new technology will automatically produce a desired social outcome. The "socio-technical vicious cycle" described in the introduction is a classic example of this failure: high-end platforms designed in urban centers collide with the social reality of low digital literacy and the technical reality of poor infrastructure, leading to low adoption, frustration, and a reinforcement of the digital divide.

Our study was an explicit and deliberate attempt to engineer a "socio-technical virtuous cycle" by designing the technology and the social implementation strategy in concert. The frugal technical design of Lentera—its offline-first architecture, trickle-syncing, and P2P sharing—was a direct response to the technical constraints of the environment. However, this technical design was co-developed with a social implementation strategy centered on teacher empowerment and community building. The co-design workshops were not just for gathering user requirements; they were a mechanism for building ownership, trust, and collective efficacy among the teachers who would become the system's champions. The training focused not just on the technical "how-to" of the tablet, but on the pedagogical "why-to" of integrating it into a new, student-centered approach.<sup>17</sup>

The peer-to-peer sharing feature is the epitome of this socio-technical synergy. It was not just a clever technical workaround for a connectivity problem; it

was a powerful social mechanism that actively fostered collaboration and created a local network of professional support among teachers. As described by one teacher, the weekly "hunt for signal" and subsequent sharing of new modules became a moment of social cohesion, collective achievement, and shared identity.<sup>18</sup> This process built a tangible sense of collective efficacy—the shared belief among the group of teachers that they could, together, overcome challenges and improve student learning. The technology, therefore, did not just deliver information; it mediated a new set of positive social interactions and professional practices. The improved learning outcomes were not a direct result of the technology alone, but an emergent property of this new, more functional socio-technical system, where a contextually appropriate tool enabled and reinforced a more effective pedagogical approach practiced by a collaborative, empowered community of educators.<sup>18</sup>

Finally, this study forces a critical re-evaluation of what constitutes "value" and "innovation" in the field of educational technology. The dominant narrative, heavily influenced by Silicon Valley ideologies and venture capital funding models, often equates innovation with technological novelty and complexity.<sup>19</sup> The most celebrated platforms are those that incorporate the latest buzzwords—artificial intelligence, machine learning, virtual reality, adaptive algorithms. Success is measured in terms of user engagement metrics, data analytics, and global scalability.

Our research offers a powerful counternarrative. The Lentera system was innovative not because it used cutting-edge technology—its components were deliberately simple and robust—but because it offered a novel and effective solution to a deeply entrenched, context-specific problem. Its innovation was architectural and conceptual, not merely functional. It redefined the problem from "how can we deliver high-quality streaming video to remote schools?" to "how can we create a resilient, self-sustaining ecosystem of learning resources that can function with minimal to no internet?". This shift in perspective is the essence of frugal innovation.

The value of Lentera was not measured in the terabytes of data it collected, but in the quality of the human interactions it enabled—the small-group instruction, the peer collaboration, the teacher's newfound ability to connect with a struggling student, and the emergence of a professional learning community.<sup>19</sup> This suggests that the true measure of an educational technology's worth is not its technical sophistication, but its pedagogical utility and its ability to empower the human actors within the educational system.

This has profound implications for policy and practice. It calls for a move away from purely market-driven models towards more public-interest-oriented approaches to EdTech development and funding. It suggests that impact evaluations must look beyond simple test scores to measure changes in teaching practices, student engagement, and teacher collaboration. It argues for the importance of long-term, embedded, design-based research over short-term, decontextualized trials.<sup>20</sup>

While this study provides robust evidence for the effectiveness of the frugal innovation approach, it is not without limitations. The quasi-experimental design, while strong, is susceptible to the Hawthorne effect, where participants' awareness of being studied may influence their behavior. The study's duration of one academic year demonstrates significant gains, but questions about the long-term sustainability of these effects remain. Furthermore, while Maluku is representative of many remote Indonesian regions, the specific cultural and social dynamics of the communities studied mean that generalizability to all contexts must be approached with caution.

A critical area for future work is the exploration of long-term financial sustainability. The current model relies on research funding for devices and development.<sup>20</sup> A scalable model might involve partnerships with the Indonesian Ministry of Education, integrating Lentera into the national budget for educational resources in disadvantaged regions. Another avenue could be a non-profit foundation model, supported by corporate social responsibility initiatives, that could manage content updates and teacher support networks. Exploring

these pathways is an essential next step to move from a successful pilot to a transformative, at-scale solution.

## 5. Conclusion

This research journey began with a fundamental challenge: the stark reality of educational inequity in remote Indonesia, a problem paradoxically worsened by the very digital tools designed to solve it. In response, this study did not just diagnose the problem but engineered a solution, adopting a frugal innovation approach to create "Lentera," a learning system born from its context. The result was not merely a piece of functional software, but a vibrant proof of concept that technology, when designed with humility, empathy, and a relentless focus on the user, can be a powerful force for equity.

We demonstrated conclusively that a context-aware, low-bandwidth, and asynchronous system was not only feasible to implement but was embraced with enthusiasm by teachers and students, becoming woven into the very fabric of the classroom. The ultimate vindication of this approach lies in the significant and meaningful improvements in foundational literacy and numeracy. These were not abstract statistical gains; they represent real children in some of the most overlooked communities unlocking new potentials and being given a fairer chance to succeed. Our findings reveal that the system's true power was its role as a catalyst, overcoming infrastructural barriers to unleash the pedagogical potential of teachers. It provided the missing tool that allowed the ambitious national vision of *Merdeka Belajar* to take root in the soil of the most challenging educational landscapes.

The central conclusion of this work is therefore both a challenge and an invitation. It challenges the dominant, resource-intensive paradigm of educational technology and proves that effective, high-quality digital learning is possible even in the most difficult settings. It is an invitation to policymakers, educators, and engineers to rethink innovation not as a race for technical supremacy, but as a creative and collaborative search for what truly empowers people. The story of Lentera illustrates that by embracing

constraints not as limitations but as a catalyst for creativity, we can design solutions that are not only more sustainable and accessible but are also more profoundly aligned with the beautiful, complex, and human dynamics of teaching and learning. It shows that we can, and must, engineer for resilience and simplicity to close the digital divide and ensure the lantern of learning shines brightly and equitably in every classroom, regardless of its location on the map.

## 6. References

1. Chen L-T, Liu L, Tretheway P. Using multilayer videos for remote learning: Videos of session guidance, content instruction, and activity. *Comput Sch.* 2021; 38(4): 322–53.
2. Womack TA, Monteiro EM. Special education staff well-being and the effectiveness of remote services during the COVID-19 pandemic. *Psychol Sch.* 2022; 60(5): 1374–93.
3. Gershby N, Katz I. Students engagement in remote-learning during the COVID-19 crisis: The role of the support provided to teachers and the parent–teacher relationship. *Psychol Sch.* 2023; 60(11): 4293–311.
4. Mire SS, Keller-Margulis MA, Izuno-Garcia AK, Jellinek ER, Loria Garro ES. Evaluating the feasibility of remotely administered curriculum-based measurement for students with autism: a pilot study. *Psychol Sch.* 2023; 60(2): 345–63.
5. Turner B, Bullock S, Butler S, Ferrington L, Macartney M, Major L, et al. The Murray-Darling Medical Schools Network Research Collaboration: protocol for a longitudinal, multi-university program of work to explore the effect of rurally based medical school programs in the Murray-Darling region. *Rural Remote Health.* 2024; 24(1): 8306.
6. Hunter-Mullis K, Qing C, Decker KA. Evaluation of remote and in-person instruction of a social-emotional learning curriculum in a rural midwestern middle school: a case study. *Psychol Sch.* 2024.
7. Ningrum DA, Budiyo B, Utanto Y. Constructing an indigenous ecological curriculum: educational practices of the Sedulur Sikep community. *Indones J Curriculum Educ Technol Stud.* 2025; 13(1).
8. Firat M. A global triangulation approach to ChatGPT integration in education. *Educ Technol Q.* 2025; 2025(2): 134–50.
9. Danzan T, Sambuu U, Chuluunbat M, Avkhinsukh T, Sandag E. ICT readiness of secondary school teachers: Mongolian case study. *Contemp Educ Technol.* 2025; 17(3): ep586.
10. Yang T, Cheon J, Cho M-H, Huang M, Cusson N. Undergraduate students' perspectives of generative AI ethics. *Int J Educ Technol High Educ.* 2025; 22(1).
11. Abramenska-Lachheb V, Lachheb A, Ozogul G. Value-sensitive design in the praxis of instructional design: a view of designers in situ. *Br J Educ Technol.* 2025; 56(4): 1311–49.
12. Prieto LP, Viberg O, Yip JC, Topali P. Aligning human values and educational technologies with value-sensitive design. *Br J Educ Technol.* 2025; 56(4): 1299–310.
13. Ishmuradova II, Zhdanov SP, Kondrashev SV, Erokhova NS, Grishnova EE, Volosova NY. Pre-service science teachers' perception on using generative artificial intelligence in science education. *Contemp Educ Technol.* 2025; 17(3): ep579.
14. Fu H, Xu M, Wu Y, Wang W. What facilitates frugal innovation? – A configurational study on the antecedent conditions using fsQCA. *J Innov Knowl.* 2024; 9(3): 100522.
15. Saleem I, Al-Breiki NSS, Asad M. The nexus of artificial intelligence, frugal innovation and business model innovation to nurture internationalization: a survey of SME's readiness. *J Open Innov.* 2024; 10(3): 100326.
16. Thai LM, Miyazaki K. Frugal innovation for smart connected products: a case study of IoT-based smart farming by Vietnamese startups. *Asian J Technol Innov.* 2025; 33(1): 313–37.

17. Mangi TA, Wei Z, Zhang L, Bao Y, Khoso WM. Profiting from frugal innovation: a strategy-tripod-view and evidence from China. *Creat Innov Manag*. 2025.
18. Pineda-Escobar MA. How to identify frugal innovation: make it relative and contextual. *Int J Innov Sci*. 2025.
19. Natasha S. Frugal business model innovation in an Indian emerging market: a multiple case study. *Asia Pac J Innov Entrep*. 2025; 19(2): 167–85.
20. Chandran N, Brahmachari SK. Technology, knowledge and markets: connecting the dots—electric rickshaw in India as a case study. *J Frugal Innov*. 2015; 1(1).