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

Hesti Putri[1], Maya Enderson[2*], Jasmila Tanjung[3], Matilda Munoz[4], Sarah Armalia[5], Jovanka Andina[6], Kevin Setiawan[7], Sudarto Sudarto[8], Khalil Jibran[9], Jasmine Alieva[10]

[1]Department of Informatics Science, CMHC Research Center, Palembang, Indonesia
[2]Department of Architecture, Enigma Institute, Palembang, Indonesia
[3]Department of Environmental Engineering, CMHC Research Center, Palembang, Indonesia
[4]Department of Physics, Camphece Science Center, Campeche, Mexico
[5]Department of Natural Sciences, Barelang Study Center, Tanjung Pinang, Indonesia
[6]Department of Civil Engineering, CMHC Research Center, Palembang, Indonesia
[7]Department of Chemical Engineering, CMHC Research Center, Palembang, Indonesia
[8]Department of Botanical Sciences, CMHC Research Center, Palembang, Indonesia
[9]Department of Chemical Science, CMHC Research Center, Palembang, Indonesia
[10]Department of Industrial Engineering, Yevlakh Study Center, Yevlakh, Azerbaijan

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Corresponding author
Maya Enderson
maya.enderson@enigma.or.id

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0009-0002-7147-1988

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ABSTRACT

Background. Educational technology (EdTech) is often said to democratize learning in Indonesia. In remote island regions the promise falls short: poor connectivity and thin infrastructure keep the digital divide in place. Frugal innovation builds effective solutions from limited resources and may offer a context-aware response.

Objective. We designed, implemented, and evaluated "Lentera", a low-bandwidth, asynchronous, offline-first learning system for primary literacy and numeracy in remote Indonesian schools.

Methods. Mixed-methods Design-Based Research came first. A school-level controlled evaluation followed over one academic year in six primary schools in the Maluku Islands (three intervention, three control; 302 students; 34 teachers). Data comprised literacy and numeracy pretests and posttests, System Usability Scale (SUS) surveys, usage logs, interviews with 18 teachers, and more than 80 hours of classroom observation. Students were nested in schools, so we fitted a two-level Hierarchical Linear Model (HLM).

Results. Lentera was feasible to implement. Teachers received more than twice as many modules through offline peer-to-peer sharing as through internet downloads. After controlling for pretest scores, the intervention group scored higher in literacy ($\gamma = 11.85$, $p < 0.001$) and numeracy ($\gamma = 12.91$, $p < 0.001$). Mean SUS scores were 81.2 (teachers) and 75.8 (students). Interviews and observations described more student-centered, differentiated teaching and closer collaboration among teachers.

Conclusion. A frugally designed, offline-first learning system was feasible. It was associated with higher literacy and numeracy in remote schools, in line with the aims of Kurikulum Merdeka. Replication with more schools is needed before the effects can be generalized.

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1. Introduction

Indonesia is an archipelago of more than 17,000 islands. Over the past several decades it has made large gains in access to basic education. Quality has not kept pace, and many observers now speak of a persistent "learning crisis". In international assessments such as the Programme for International Student Assessment (PISA), Indonesian students repeatedly fall in the lower quartiles on foundational skills like literacy and numeracy. Going to school, in other words, does not reliably turn into learning.[1,2]

The gap between well-resourced urban centers, such as those on Java, and isolated rural and remote regions is wide and defining. Schools in the remote east of the archipelago face many problems at once. Facilities are poor. Good learning materials are chronically scarce, and trained, supported teachers are in short supply.[3,4] Poor connectivity, limited facilities, and educator shortages have been documented in frontier, outermost, and disadvantaged regions.[5] Against this background of deep inequity, educational technology (EdTech) has been presented as a possible remedy. The COVID-19 pandemic then sped up the growth of a lively Indonesian EdTech market, and large sums went into platforms meant to digitize learning.

Many platforms in this market, however, assume stable, fast internet and high digital literacy. In the regions that stand to gain most, they have often been ineffective and exclusionary.[6–8] Remote instruction by video or online delivery has been evaluated in several rural and school settings.[9,10] We describe the

result as a "socio-technical vicious cycle". Communities that most need what EdTech can offer are the least able, in infrastructure and in income, to reach it. The educational gap does not narrow. It may widen, because technology can deepen the inequalities it was supposed to ease. Teachers' readiness for technology also varies widely.[11]

This study set out to break that cycle. We drew on frugal innovation, a design philosophy that builds effective, high-value solutions from limited resources by deliberately keeping complexity and cost low.[12–14] Most work on the concept comes from business and technology settings,[15–18] although frugal approaches have also been proposed for education.[19] We chose to design for the world as it is in remote Indonesia, not for an idealized, well-connected one. The work took place within Indonesia's national education reform, the Merdeka Belajar (Emancipated Learning) policy, implemented through the Kurikulum Merdeka curriculum. The policy asks for a move from rote memorization toward student-centered, differentiated, and competency-based learning.[20–22] Our expectation was that a frugally designed tool, built in direct response to local constraints, could help make that reform workable by giving teachers the resources to carry out its pedagogical vision.

What is new here is the deliberate and systematic use of frugal innovation as the guide for both technological design and social implementation, combined with a field evaluation in the demanding setting of remote Indonesian schools. Design-Based Research (DBR) lets iterative design be joined to systematic evaluation in real settings.[23–25] The outcome is a practical artifact, the "Lentera" learning system, and an account of how technology can be fitted to its context to advance educational equity. The study had three aims that shaped every phase. The first was to design and develop, with educators, a low-bandwidth, asynchronous, offline-capable digital learning system (named "Lentera", the Indonesian word for lantern), based on frugal innovation and aligned with the pedagogical goals of Kurikulum Merdeka. The second was to implement the system in a real, resource-constrained primary school setting in remote Indonesia and to evaluate its feasibility, usability, and adoption by teachers and students. The third was to estimate its effect on literacy and numeracy by comparing intervention and control schools with a school-level controlled design and multilevel statistical analysis.

2. Methods

2.1 Study design

The research was planned in four sequential phases over 18 months. It used a multi-phase, mixed-methods Design-Based Research (DBR) approach. DBR suits this work for two reasons.[23–25] It supports the iterative development and refinement of an educational intervention (the "Lentera" system) in a real setting. It also yields theoretical insight about learning and technology integration in such settings. The original submission described the design as quasi-experimental, yet schools were assigned by a random sequence. It is therefore reported here as a school-level controlled study. Guidelines exist for reporting both cluster-randomized and non-randomized evaluations.[26,27]

2.2 Phase 1: Contextual inquiry and needs analysis

The first phase was a contextual inquiry into the educational, social, and technical environment of the target communities. Our team carried out ethnographic fieldwork in selected communities in Maluku province. We chose the region for its archipelagic geography, cultural diversity, and marked developmental disparities, which make it a representative case of eastern Indonesia. The fieldwork included 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, and the questions concerned daily teaching practice, curricular challenges, available resources, and community attitudes toward education and technology.

A technical audit ran alongside the fieldwork to map the digital landscape. We measured mobile signal strength (2G, 3G, 4G) and ran data speed tests at different times of day in and around the schools. Weak mobile data signals were sometimes available, though only briefly and often after a walk to a particular hilltop or coastal point. Reliable, continuous internet suitable for streaming or large downloads was entirely absent inside the schools. This finding settled our choice of an offline-first, asynchronous architecture.

2.3 Phase 2: Co-design and system development

The needs analysis gave us rich data, and a six-month co-design process followed to develop the "Lentera" (Lantern) learning system. Three principles of frugal innovation guided it: minimize complexity, maximize resourcefulness, and concentrate on core functions. The system became a lightweight, standalone Android application whose priority was asynchronous, offline use on low-cost tablets.

Content centered on foundational literacy and numeracy for the primary grades. Every module, quiz, and activity was tied to the competency-based structure of Kurikulum Merdeka. To keep the material relevant and give teachers ownership, we held four participatory design workshops with the 18 teachers, following co-design principles[28–31] from the schools that later formed the intervention group. The workshops were more than feedback sessions. Teachers helped shape the user interface and chose content, and above all they worked out ways around the connectivity problem.

This joint work produced the main architectural features of Lentera:

"Trickle-Syncing": a background service. Whenever it detects even a minimal data connection, it downloads highly compressed content modules patiently and intelligently, without any action from the user.

Offline Peer-to-Peer Sharing: devices pass downloaded modules to other devices with no connection at all, using Wi-Fi Direct or Bluetooth. One teacher's successful download thus became a resource for the whole school.

Concrete Learning Modules: content was built to be interactive and engaging. A Grade 2 literacy module taught syllables (suku kata) through a game in which students dragged and dropped syllables to form words that matched images of local fauna. A Grade 4 numeracy module borrowed the idea of a local market stall for gamified quizzes on multiplication and division, with familiar goods such as fish and spices. Grounding learning content in local culture and environment has precedent in Indonesian curriculum work.[32]

2.4 Phase 3: Implementation and evaluation

Setting and Participants: We recruited a purposive sample of six public primary schools from two island districts in Maluku province. Both districts depend largely on subsistence fishing and agriculture, and public infrastructure, electricity included, is limited and often unreliable. Teacher qualifications there are frequently below the national average, and multi-grade teaching is common. We matched the six schools into three pairs on school size, student-to-teacher ratio, existing community resources, and the complete absence of reliable internet. Within each pair, a computer-generated random sequence assigned one school to the intervention group and the other to the control group. This approach gave an intervention group of three schools, with 18 teachers and 154 students, and a control group of three schools, with 16 teachers and 148 students.

Intervention and Training: Each of the 18 intervention teachers received a low-cost Android tablet with the Lentera application pre-installed. Before the academic year began they also

attended a two-day training workshop. The training protocol had been planned with care:

Day 1: Technical Familiarization. The aim was confidence with the hardware and software, and topics were basic tablet operation, moving around the Lentera interface, managing content modules, and practicing the offline peer-to-peer sharing feature.

Day 2: Pedagogical Integration. Here the focus moved from "how to use" the tool to "how to teach" with it. We introduced strategies aligned with Kurikulum Merdeka, including rotational learning stations, small-group targeted instruction with Lentera, and lesson plans that mix digital activities with traditional hands-on work. The control schools received no intervention. They kept their usual teaching, which typically relied on a single textbook and whole-class lecturing.

2.5 Data collection

Data Collection Strategy: We designed a many-sided strategy to capture the whole picture of the intervention's impact.

Learning Outcomes: All students in both groups sat the Indonesian Foundational Learning Assessment for Primary (IFLAP), an instrument described by the authors as standardized and culturally validated, as a pretest and posttest 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, which gauges perceived ease of use.

System Usage: The Lentera application logged anonymized usage data passively, and these data included the number and type of modules accessed, session durations, and how often content arrived by internet download rather than peer-to-peer sharing.

Qualitative Data: To follow the process of adoption and its effect on teaching, we held post-intervention semi-structured interviews with all 18 intervention teachers, and a second round of intensive classroom observations took place in the intervention schools.

2.6 Phase 4: Data analysis

The last two months went to a full mixed-methods analysis. Students were nested within schools, so the learning outcomes were analyzed with a two-level Hierarchical Linear Model (HLM). This approach accounts for the non-independence of observations. It also gives a more accurate estimate of the intervention effect by splitting variance between the student and school levels. We first computed the Intraclass Correlation Coefficient (ICC) from an unconditional model. The ICC shows what share of the variance in posttest scores lies at the school level and so confirms whether a multilevel model is needed. The unconditional model was specified as:

$$Y_{ij} = \beta_{0j} + r_{ij}$$
$$\beta_{0j} = \gamma_{00} + u_{0j}$$

where Y_{ij} is the posttest score of student i in school j.

The main analysis used a two-level random-intercepts model with the student's posttest score as the outcome. To control for prior ability, the pretest score entered at Level 1 as a covariate (group-mean centered). Intervention status (1 = Intervention, 0 = Control) was the key Level 2 predictor. The final fitted model was specified as:

$$\text{PostTest}_{ij} = \beta_{0j} + \beta_{1j}(\text{PreTest}_{ij} - \text{PreTest}_{j}) + r_{ij}$$
$$\beta_{0j} = \gamma_{00} + \gamma_{01}(\text{Intervention}_{j}) + u_{0j}$$
$$\beta_{1j} = \gamma_{10}$$

Here, γ_{01} is the estimated average difference in posttest scores between the intervention and control groups, controlling for pretest scores. The SUS surveys and the system usage logs were analyzed with descriptive statistics. With only six schools, school-level tests rest on few degrees of freedom, and small-sample corrections are advisable.[33–36]

Interview transcripts and observation field notes were analyzed together by thematic analysis.[37] We built an initial coding framework from the research questions. Two researchers coded a subset of the data on their own to establish inter-coder reliability.[38] They then discussed and settled any discrepancies and refined the final framework. That framework was applied to the full dataset to identify the main themes: pedagogical change, teacher collaboration, and student engagement.

2.7 Ethical considerations

Regional educational authorities and the institutional review board of the Enigma Institute approved the study protocol (Approval number 2024/102). All participating teachers, and the guardians of all student participants, gave informed written consent.

3. Results

3.1 Feasibility and usability

Deployment was feasible: usage logs showed sustained use by teachers and students across the ten-month academic year, and Table 1 gives the figures. The usage patterns fit the frugal design philosophy. Peer-to-peer (P2P) sharing was an important route for content distribution. On average, teachers received more than twice as many modules through local offline sharing as through direct internet downloads (Table 1). This indicates that the design worked within the severe connectivity limits of the setting. Observation showed teachers working the devices creatively into daily routines: individual student work, collaborative small-group activities, and whole-class instruction with the tablet screen shown through low-cost portable projectors. One teacher described the social meaning of the P2P feature:

> *"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)	SD	Total (across all users)
Modules downloaded (via internet)	24.5	6.2	441
Modules received (via P2P sharing)	58.3	12.5	1,049
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	6,960

Note. SD = standard deviation. Totals follow from the per-teacher means (for example, 24.5 × 18 = 441).

Users rated Lentera's usability very favorably. The 18 teachers gave a mean System Usability Scale (SUS) score of 81.2 (SD = 6.5), and the 50 surveyed students gave 75.8 (SD = 8.2). The unweighted mean of the two group means was 78.5; weighted by the number of respondents it was 77.2. Both values are above the commonly cited average of 68 and fall in the "B+" grade range of published SUS norms,[39–41] which indicates high perceived usability. Interviews and observations agreed. Teachers and students repeatedly praised the simple, icon-based navigation and the uncluttered interface. One teacher compared 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."*

3.2 Learning outcomes

The intervention group showed larger gains in student learning than the control group. Table 2 gives the pre- and posttest scores for the intervention and control groups. Both groups began at almost identical baselines in literacy and numeracy. Over the academic year the intervention group made larger gains: in literacy, 16.3 points against 4.3 in the control group; in numeracy, 16.5 against 3.7. From the printed means and pooled SDs, the standardized posttest differences were about 1.25 (literacy) and 1.34 (numeracy).

Table 2. Pretest and posttest scores for literacy and numeracy by group.

Assessment	Group	*N*	Pretest, mean (SD)	Posttest, mean (SD)
Literacy	Intervention	154	52.4 (10.1)	68.7 (9.8)
	Control	148	51.9 (10.5)	56.2 (10.2)
Numeracy	Intervention	154	48.6 (9.8)	65.1 (9.5)
	Control	148	48.1 (10.2)	51.8 (10.3)

Note. Values are mean (SD). Scores were obtained with the IFLAP. Mean gains: literacy, 16.3 (intervention) and 4.3 (control); numeracy, 16.5 and 3.7.

An unconditional HLM analysis came first. It showed that clustering by school explained a considerable part of the variance in posttest scores, for literacy (ICC = 0.21) and for numeracy (ICC = 0.19), which supported a multilevel approach.[42] The main HLM analysis, controlling for pretest scores, found a positive association of the Lentera intervention with learning outcomes. Table 3 gives the full results of the two-level Hierarchical Linear Model (HLM) analysis for literacy and numeracy. The model was built to isolate the unique effect of the intervention while holding constant two things: students' prior academic ability, and the grouping of students within schools.

The literacy model shows a clear pattern of growth. Its fixed-effects coefficients are average effects across all schools. The Intercept (γ_{00} = 56.41) sets a baseline. It is the estimated average literacy posttest score of a student in a control school with an average pretest score, and everything else is read against it. The Pretest Slope (γ_{10} = 0.81) confirms a strong positive link between prior knowledge and end-of-year results. Each one-point rise in the literacy pretest score predicts a posttest score 0.81 points higher. Baseline knowledge must be accounted for. The Intervention effect (γ_{01} = 11.85) is the most important finding of the study. After controlling for initial pretest scores, students in the Lentera group scored on average 11.85 points higher on the literacy posttest than their control-group peers. The difference is statistically significant ($p < 0.001$); a difference this large would be unlikely if the intervention had no effect.[43] The result is consistent with a positive effect of the intervention on literacy. The Variance Components show how variability in scores is distributed. The School-Level Variance (τ_{00} = 9.87) indicates that average literacy scores differ between schools, which supports the multilevel model.

The numeracy model mirrors the literacy results. The Intercept (γ_{00} = 52.03) is the numeracy baseline, the predicted posttest score of an average student in a control school. The Pretest Slope (γ_{10} = 0.85) is again strong and positive, so students with higher initial numeracy skills also scored higher at posttest. The Intervention effect (γ_{01} = 12.91) is larger still. Students who used Lentera scored 12.91 points higher on the numeracy posttest than control students, holding pretest scores constant, and this difference is also statistically significant ($p < 0.001$). As in the literacy model, the School-Level Variance (τ_{00} = 11.21) is considerable. School-level factors again appear to contribute to differences in student outcomes, which supports the HLM approach.

In sum, the HLM analysis shows a large, positive, statistically significant association of the Lentera intervention with achievement in both foundational literacy and numeracy. The same pattern appears in two different domains. This suggests that the pedagogical changes Lentera made possible may have contributed to accelerated learning in this resource-constrained setting. Because the comparison rests on six schools and one academic year, the size of the effect should be treated with caution until it is replicated.

Table 3. Hierarchical Linear Model results for the effect of the Lentera intervention on posttest scores.

Model and predictor	Coefficient (γ)	SE	*t*-ratio	*p*
Literacy outcomes model				
Fixed effects				
Intercept (γ_{00})	56.41	0.88	64.10	< 0.001
Intervention (γ_{01})	11.85	1.25	9.48	< 0.001
Pretest slope (γ_{10})	0.81	0.04	20.25	< 0.001
Variance components				
School-level variance (τ_{00})	9.87			
Student-level variance (σ^2)	37.45			
Numeracy outcomes model				
Fixed effects				
Intercept (γ_{00})	52.03	0.91	57.18	< 0.001
Intervention (γ_{01})	12.91	1.31	9.85	< 0.001
Pretest slope (γ_{10})	0.85	0.05	17.00	< 0.001
Variance components				
School-level variance (τ_{00})	11.21			
Student-level variance (σ^2)	41.50			

Note. γ = fixed-effect coefficient; SE = standard error; τ_{00} = school-level variance; σ^2 = student-level variance. Students, n = 302; schools, n = 6 (three per group). Pretest was group-mean centered.

3.3 Qualitative findings

Teacher interviews and classroom observations offer an account of how the gains may have come about. Teachers attributed them mainly to pedagogical changes that the tool made possible, not to the technology itself. Teachers said Lentera was the enabling tool that let them, for the first time, put differentiated instruction into practice effectively. Differentiated instruction is 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."*

Observation was consistent with these accounts. We saw a move from teacher-centered, whole-class lectures to a more student-centered learning environment. Students often worked in small groups around a tablet, debating quiz answers or helping a peer through a module. This built academic skills, and it also built collaboration and communication. One observation is worth describing. A shy girl who rarely spoke in class was working with a partner on a Lentera literacy game. She became animated. She pointed out correct answers with confidence and explained her reasoning to her classmate. The technology appeared to give her a new and less intimidating way to show her competence.

Another teacher pointed out 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 findings suggest that Lentera was used less as a digital textbook than as a catalyst for changes in classroom organization. It appeared to lift part of the logistical burden of differentiation from the teacher, leaving more room for facilitation and for the pedagogy that national policy promotes.

4. Discussion

4.1 Principal findings

The findings offer a nuanced account of the role of technology in resource-constrained educational settings. Lentera worked as a functional application, and its design reflects a different philosophy from the high-bandwidth platforms that dominate much of the EdTech market. The discussion follows four intertwined threads: the validation of frugal innovation as a design paradigm, technology as a catalyst for profound pedagogical reform, the engineering of a virtuous socio-technical cycle, and the resulting question of what counts as "value" and "innovation" in the pursuit of educational equity.

The feasibility of Lentera appears to follow from its founding philosophy, frugal innovation. The aim was never a cheaper, "good enough" substitute for "real" EdTech. It was an intelligent, empathetic, and disciplined reframing of the problem. In our view, much EdTech development equates progress with feature complexity, data intensity, and ever-higher bandwidth, and such platforms can prove impractical in places like remote Indonesia, where they presuppose always-on infrastructure.[6–8] We did not compare Lentera with commercial platforms, so our data cannot show that this paradigm is counterproductive. They show that, in these six schools, a design without such requirements could be implemented and used.

4.2 The offline-first architecture

The most informative quantitative finding of the study was that teachers received more than double the educational content through offline peer-to-peer sharing than through direct internet downloads. This is consistent with the expectation that in a low-connectivity environment an asynchronous, offline-first architecture is a precondition for feasibility and adoption,

in line with other offline and local-network approaches in low-resource schools.[44–47] Reports describe offline micro-servers and tablets delivering learning content without internet at modest cost, whereas we found little published evidence on device-to-device sharing of the kind used here. The architectural choice addressed the main infrastructural barrier that has limited EdTech initiatives in Indonesia. A platform that demands constant, stable connectivity for authentication, content streaming, and data synchronization would probably be difficult to use in these schools. Lentera was engineered for the opposite reality. Its "trickle-sync" capability was designed to "sip" compressed data patiently whenever a fleeting, low-quality connection appeared. An infrastructural liability became a usable asset.

Once the modules were on a single device, the system turned into a self-contained, self-propagating learning ecosystem. Peer-to-peer sharing converted a technological constraint into a powerful social asset. A culture of collaboration grew from it. This departs from a common assumption in the technology sector that the context (infrastructure, market) should be waited on to catch up with the technology. Lentera offers an alternative: design for the constraints of the real world, not for idealized conditions.

4.3 Simplicity and usability

The high usability scores (mean SUS of 81.2 among teachers and 75.8 among students) point to another tenet of frugal innovation, the disciplined pursuit of simplicity.[12–14] Many products suffer from "feature creep". Lentera's design was deliberately subtractive. The co-design process with teachers was a long exercise in stripping away every non-essential function, every confusing menu, and every extraneous button. The goal was a clean, intuitive, icon-driven interface that kept cognitive load low for teachers and students, many of whom had limited prior digital literacy. Simplicity was not a compromise. It was probably an important factor in rapid adoption and proficiency. Teachers noted that the ease of use let them spend their finite mental energy on the pedagogical use of the tool, not on technical troubleshooting. A lesson for inclusive technology follows: accessibility is more than physical access to a device, and it also means that the functions of the device are cognitively accessible.

4.4 Learning outcomes and pedagogical change

Feasibility aside, the most important finding was the statistically significant and large difference in literacy and numeracy between intervention and control schools. Effects of this size are well above those usually reported for educational technology in low- and middle-income countries,[48–50] so they call for replication and for a check of the summary statistics against the raw data. The qualitative data offer one possible explanation: teachers described Lentera as a catalyst that helped them begin to implement the principles of the Merdeka Belajar reform in a way that had been difficult before.

The Kurikulum Merdeka asks for a move away from a one-size-fits-all, lecture-based model. In its place it puts a student-centered, differentiated approach, often described as "teaching at the right level".[22,51] Teachers must assess the competency level of each student and then tailor their instruction. The goal is well supported by evidence. Putting it into practice in a typical remote Indonesian classroom poses an enormous logistical challenge. One teacher is often responsible for several grades. Teaching aids are limited, and student abilities span a wide range. Teachers simply lack the time and resources to prepare dozens of lesson plans and worksheets to meet each student's needs.

This is the systemic bottleneck that Lentera was designed to address. It offers a curated, curriculum-aligned library of self-paced digital modules. In this way it took part of the burden of content creation and differentiation off the individual teacher. It was a ready-made tool that let students work independently, at their own pace, on material suited to their learning level. Teachers described a change in the classroom dynamic and more time and attention for individual pupils. Teachers were observed moving around the room, facilitating small-group work, and giving intensive, targeted support to the students who needed it most. The technology did not replace the teacher. It augmented and empowered the teacher, who could take on higher-order tasks such as facilitating, mentoring, and inspiring. The remark of one teacher that the classroom had become one with "everyone learning at their own level" illustrates this change, although it is one account among many. Adaptive learning technology has likewise been associated with changes in teachers' classroom management in primary schools.[52]

4.5 A socio-technical interpretation

Socio-technical systems theory offers a useful lens on the results of Lentera. It holds that technological artifacts and social structures are not separate. They are intertwined and mutually constitutive. Many technology projects in development contexts fail because of a naive "technological determinism", the belief that introducing a new technology will automatically produce the desired social outcome.[53] The "socio-technical vicious cycle" described in the introduction illustrates this. High-end platforms designed in urban centers collide with the social reality of low digital literacy and the technical reality of poor infrastructure. Adoption is low, frustration is high, and the digital divide is reinforced.

Our study was a deliberate attempt to create a "socio-technical virtuous cycle", with technology and social implementation strategy designed together. The frugal technical design of Lentera (offline-first architecture, trickle-syncing, and P2P sharing) answered the technical constraints of the environment directly. It was co-developed with a social implementation strategy built on teacher empowerment and community building. The co-design workshops did more than collect user requirements. They appear to have built ownership and trust among the teachers who would become the system's champions, in line with accounts of co-design in educational technology.[28–31] Support for teachers has also been linked to student engagement in remote learning.[54] Training covered the technical "how-to" of the tablet and also the pedagogical "why-to" of fitting it into a new, student-centered approach.

The peer-to-peer sharing feature illustrates this socio-technical interplay. It was a technical workaround for a connectivity problem, and it also appears to have worked as a social mechanism that encouraged collaboration and created a local network of professional support among teachers.[55] One teacher described the weekly "hunt for signal" and the sharing of new modules afterward as a moment of social cohesion, collective achievement, and shared identity. Teachers' accounts suggest a sense of collective efficacy, the shared belief within a group of teachers that together they could overcome challenges and improve student learning,[56,57] although collective efficacy was not measured. The technology did more than deliver information. It mediated a new set of positive social interactions and professional practices. The improved learning outcomes may therefore not be a direct result of the technology alone. They may reflect a more functional socio-technical system, in which a contextually appropriate tool enabled and reinforced a more effective pedagogy, practiced by a collaborative, empowered community of educators. In Indonesia, professional learning communities have been linked to teachers' technology literacy.[58]

4.6 Value and innovation in educational technology

Finally, the study invites a rethink of what counts as "value" and "innovation" in educational technology. Much current attention goes to technological novelty, and generative artificial intelligence in particular is at the center of recent research on education.[59–61] Success is often measured by user engagement metrics, data analytics, and global scalability.

Our research offers a contrasting case. Lentera was innovative, but not because it used cutting-edge technology. Its components were deliberately simple and sturdy. It was innovative because it offered a novel solution to a long-standing, context-specific problem. Its innovation was architectural and conceptual, more than functional. The problem was redefined. The question "how can we deliver high-quality streaming video to remote schools?" became "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 characteristic of frugal innovation.[12–14]

In the experience of the teachers, Lentera's value lay less in data collected than in the human interactions it enabled: small-group instruction, peer collaboration, a teacher's newfound ability to reach a struggling student, and the emergence of a professional learning community. The measure of an educational technology's worth may therefore be its pedagogical utility and its capacity to empower the people in the system, more than its technical sophistication.

4.7 Implications, limitations, and future work

The findings have possible implications for policy and practice. They suggest that public-interest-oriented approaches to EdTech development and funding may deserve consideration alongside market-driven models. Impact evaluations may usefully look beyond test scores to changes in teaching practices, student engagement, and teacher collaboration, and long-term, embedded, design-based research may complement short-term trials.

The study has several limitations. Only six schools took part, so inference at the school level rests on few degrees of freedom, and school, teacher, and device-support effects cannot be fully separated from the intervention. The design is open to the Hawthorne effect, in which participants' awareness of being studied may change their behavior.[62] Outcome assessment was not described as blinded, and there was no follow-up after the academic year. Whether the gains of one academic year last is an open question. Maluku is illustrative of many remote Indonesian regions, yet the specific cultural and social dynamics of the communities studied mean that generalizability to all contexts must be approached with caution. Novelty effects of new technology may also fade over time.[63]

Long-term financial sustainability is a key area for future work. The current model relied on research funding for devices and development. A scalable model might involve partnerships with the Indonesian Ministry of Education, with Lentera written into the national budget for educational resources in disadvantaged regions. A non-profit foundation model is another avenue. Supported by corporate social responsibility initiatives, such a foundation could manage content updates and teacher support networks. Exploring these pathways is an important next step in moving from a pilot to an at-scale solution.

5. Conclusion

This research began with a challenge. Remote Indonesia faces deep educational inequity, and digital tools have sometimes made it worse. Using a frugal innovation approach, we created "Lentera", a learning system designed for its context. It is functional software. In these six schools it is also a proof of concept: technology built with attention to local constraints, and with teachers, can support equity.

The study indicates that a context-aware, low-bandwidth, asynchronous system was feasible to implement. Teachers and students took it up readily, and it became part of classroom routines. The approach was associated with significant gains in foundational literacy and numeracy. Those gains represent real children in some of the most overlooked communities. Our findings suggest that the system acted as a catalyst, working around infrastructural barriers and helping teachers use more differentiated pedagogy in line with the aims of Merdeka Belajar. That is a modest claim, and it needs replication.

The central conclusion is both a challenge and an invitation. The study challenges the resource-intensive paradigm of educational technology and shows that effective digital learning can be feasible even in difficult settings, which is no small matter. It invites policymakers, educators, and engineers to rethink innovation as a collaborative search for what empowers people. Embracing constraints as a source of creativity, not as limitations, may yield solutions that are more sustainable and accessible. Replication in more schools, with longer follow-up, is the next step.

Declaration

Artificial Intelligence Use Statement

No generative artificial intelligence tool was used to write or revise the text, analyze the data, create images, or generate any other scholarly content of this manuscript.

Author Contribution Statement

Conceptualization, H.P. and M.E.; methodology, H.P., M.E., and J.T.; software, K.S. and S.S.; validation, M.M. and S.A.; formal analysis, M.M. and J.An.; investigation, H.P., J.T., S.A., and J.Al.; resources, M.E. and K.J.; data curation, J.An. and K.S.; writing – original draft, H.P.; writing – review and editing, M.E., J.T., M.M., S.A., J.An., K.S., S.S., K.J., and J.Al.; visualization, S.S. and K.J.; supervision, M.E.; project administration, H.P. All authors read and approved the final manuscript.

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Conflict of Interest / Competing Interests

The authors declare that they have no competing financial or non-financial interests related to this work.

Ethics Approval and Consent to Participate

The study protocol was approved by regional educational authorities and by the institutional review board of the Enigma Institute, Indonesia (Approval number 2024/102). All participating teachers, and the guardians of all student participants, gave informed written consent.

Consent for Publication

Teacher quotations are reported without names. All participants were consented to the publication of anonymized quotations.

Data Availability Statement

The datasets generated and analyzed during this study can be obtained from the corresponding author on reasonable request.

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