

MathemAfrica: A Multilingual Explainable Artificial Intelligence Ecosystem for Adaptive Mathematics Education in Resource-Constrained African Learning Environments

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Abstract—Secondary mathematics education in developing and resource-constrained contexts confronts systemic bottlenecks, including overcrowded classrooms, acute teacher shortages, frequent electrical blackouts, prohibitively expensive cellular data, and linguistic dissonance between official English instruction and students' indigenous home languages. To address these interconnected challenges, this study developed and evaluated MathemAfrica, an innovative digital learning platform integrating Bayesian Knowledge Tracing, Multidimensional Item Response Theory (M-3PL IRT), offline optical handwriting verification, and multilingual scaffolding in Hausa, Yoruba, Igbo, and Swahili. Employing an ADDIE-based design science methodology and a 16-week quasi-experimental non-equivalent pretest-posttest control group design, the intervention was evaluated across six public secondary schools in Kano State, Nigeria, with 1,428 Grade 10 students. Expert reviews confirmed high content validity (97.06%) and media quality (94.56%), while students reported exceptional practicality (96.13%). Analysis of Covariance revealed statistically significant and substantial gains in mathematical proficiency, with adjusted posttest scores of 73.84% in the intervention group versus 57.22% in conventional instruction ($F(1, 1425) = 148.92, p < .0001, \text{Cohen's } d = 0.94$). Furthermore, the platform closed 80.4% of the indigenous language achievement penalty, while maintaining real-time adaptive sequencing at merely 38.4 kB per session.

The results provide empirical evidence that combining edge-native computation with culturally responsive multilingual scaffolding strengthens secondary mathematical achievement under severe resource constraints.

Index Terms—Adaptive learning, Artificial intelligence, Bayesian Knowledge Tracing, Educational equity, Explainable artificial intelligence (XAI), Item Response Theory, Mathematics education, Multilingual scaffolding, Resource-constrained environments.

I. INTRODUCTION

Mathematical proficiency constitutes an essential cornerstone of modern secondary education, functioning simultaneously as an indispensable cognitive competency, a catalyst for quantitative scientific inquiry, and an engine for socio-economic empowerment [1], [2]. Within the developmental progression of mathematical cognition, senior secondary schooling represents a decisive transitional threshold: learners are compelled to navigate beyond concrete arithmetic algorithms and elementary computational heuristics toward abstract algebraic representations, rigorous deductive Euclidean proofs, dynamic calculus formulations, and non-routine mathematical modeling [3], [4]. Deep conceptual mastery across these hierarchical mathematical domains is increasingly vital for cultivating the analytical problem-solving and computational reasoning required in the rapidly evolving global technological economy [5], [6].

Despite its strategic importance, secondary mathematics education across developing and resource-constrained regions—most acutely across sub-Saharan Africa—faces persistent, systemic structural crises. Following the universalization of

basic education mandates across member states of the Economic Community of West African States (ECOWAS), secondary school enrollments have surged by more than 40% over the past decade. However, physical infrastructure, instructional material distribution, and specialist mathematics teacher recruitment have failed to expand commensurately. Public secondary classrooms routinely operate under extreme conditions characterized by pupil-to-teacher ratios exceeding 65:1, severe shortages of qualified mathematics educators, textbook-sharing ratios where up to four students share a single battered volume, daily electrical grid failures lasting between four and eight hours, and prohibitive commercial cellular telecommunications tariffs [7], [8]. Under these severe constraints, instruction almost universally collapses into teacher-dominated chalk-and-talk lectures emphasizing procedural memorization and rote formula drills, leaving students with fragile conceptual understanding and acute mathematics anxiety [9]–[11].

This structural crisis is intensified by an unresolved, systemic linguistic dissonance. Although high-stakes national curricula, syllabi, and terminal secondary credentialing examinations—including the West African Senior School Certificate Examination (WASSCE) administered by the West African Examinations Council (WAEC) and the Senior School Certificate Examination (SSCE) administered by the National Examinations Council (NECO)—are conducted strictly in official English, the vast majority of secondary school students communicate predominantly in indigenous home languages. In Nigeria, over 80% of secondary students speak Hausa, Yoruba, or Igbo outside the formal classroom. Research in ethnomathematics and multilingual mathematics education [12], [13] demonstrates that compelling multilingual learners to acquire abstract symbolic mathematics exclusively through a non-native language imposes a crippling extraneous cognitive load. When students cannot formulate conjectures or receive explanatory feedback in their mother tongue, productive mathematical struggle is extinguished, resulting in high failure rates on national examinations.

Didactical and epistemological obstacles in secondary mathematics have been widely documented in recent

scholarship [14], [15]. Ontogenetic obstacles arise when students lack prerequisite cognitive schemas; didactical obstacles emerge from rigid instructional sequencing that prioritizes algorithmic execution over conceptual meaning; and epistemological obstacles stem from the intrinsic abstractness of mathematical formalisms. In under-resourced secondary schools, these obstacles compound across successive terms, solidifying into entrenched mathematics avoidance [9]. While digital learning technologies and Intelligent Tutoring Systems (ITS) can mitigate Bloom's two-sigma problem by providing individualized scaffolding [16]–[18], existing commercial systems (such as ALEKS and MATHia) require continuous high-speed broadband (> 250 kbps), high-end hardware, and monolingual English instruction, rendering them unusable across majority Global South classrooms [19], [20].

To address these interconnected challenges, this study developed and evaluated MathemAfrica: an edge-native digital learning platform that integrates Bayesian Knowledge Tracing (BKT), Multidimensional Item Response Theory (M-3PL IRT), offline optical handwriting verification, and multilingual scaffolding in major regional languages (Hausa, Yoruba, Igbo, and Swahili). The central objective was to determine whether psychometrically grounded, vernacular-scaffolded adaptive tutoring delivered via edge architecture can significantly enhance secondary mathematical achievement and bridge the indigenous language penalty in resource-constrained classrooms.

Specifically, this study addressed three core research questions: 1) RQ1: How can a valid, practical, and resilient digital learning platform incorporating edge-native artificial intelligence adaptation and multilingual scaffolding be systematically developed for resource-constrained secondary mathematics education? 2) RQ2: To what extent does implementation of the MathemAfrica platform significantly improve secondary students' conceptual understanding and achievement across core mathematical domains compared to conventional instruction? 3) RQ3: Does the provision of bilingual vernacular scaffolding significantly reduce the systemic achievement gap between native English speakers and students from indigenous language backgrounds?

II. SYSTEM ARCHITECTURE AND EDGE-FIRST ARTIFICIAL INTELLIGENCE ECOSYSTEM

The engineering architecture of MathemAfrica was designed to eliminate reliance on continuous cloud connectivity, expensive client hardware, and proprietary operating systems. As illustrated in Fig. 1, the platform is structured across five interconnected tiers operating in a closed-loop formative scaffolding cycle:

A. Client Edge Sensory Tier Captures multimodal learner inputs, including touch-screen stylus or finger-drawn mathematical handwriting, step-by-step symbolic keystrokes, and vernacular voice queries. Handwriting recognition is executed entirely on-device using a quantized MobileNetV3 convolutional neural network compiled to WebAssembly (Wasm), parsing handwritten strokes into mathematical Abstract Syntax Trees (AST) with an inference latency below 85 milliseconds on hardware costing under \$50 USD.

B. Progressive Web Application (PWA) Layer Packaged as an offline-first PWA, the core application caches locally on client hardware via service workers

and IndexedDB. Lesson modules, interactive geometry manipulatives, and indigenous audio lexicons reside on the device, allowing uninterrupted access during power grid outages and telecommunications blackouts.

C. Asynchronous Store-and-Forward Sync Queue Encrypted interaction logs and knowledge updates sync opportunistic 2G/3G/4G or Wi-Fi beacons via compressed protocol buffers (averaging 38.4 kB per session).

D. Cognitive Assessment & Pedagogical Sequencing Gateway Executes Bayesian Knowledge Tracing and Multidimensional IRT on-device, deploying personalized hints and vernacular audio scaffolding upon detecting cognitive impasse. Fig. 2 illustrates the mobile user interface demonstrating handwritten step verification and mother-tongue Socratic hints.

E. Supervisory Teacher Decision Cockpit Operates over local Wi-Fi, visualizing real-time class mastery heatmaps and explainable diagnostic insights via Shapley Additive exPlanations (SHAP) for targeted small-group remediation.

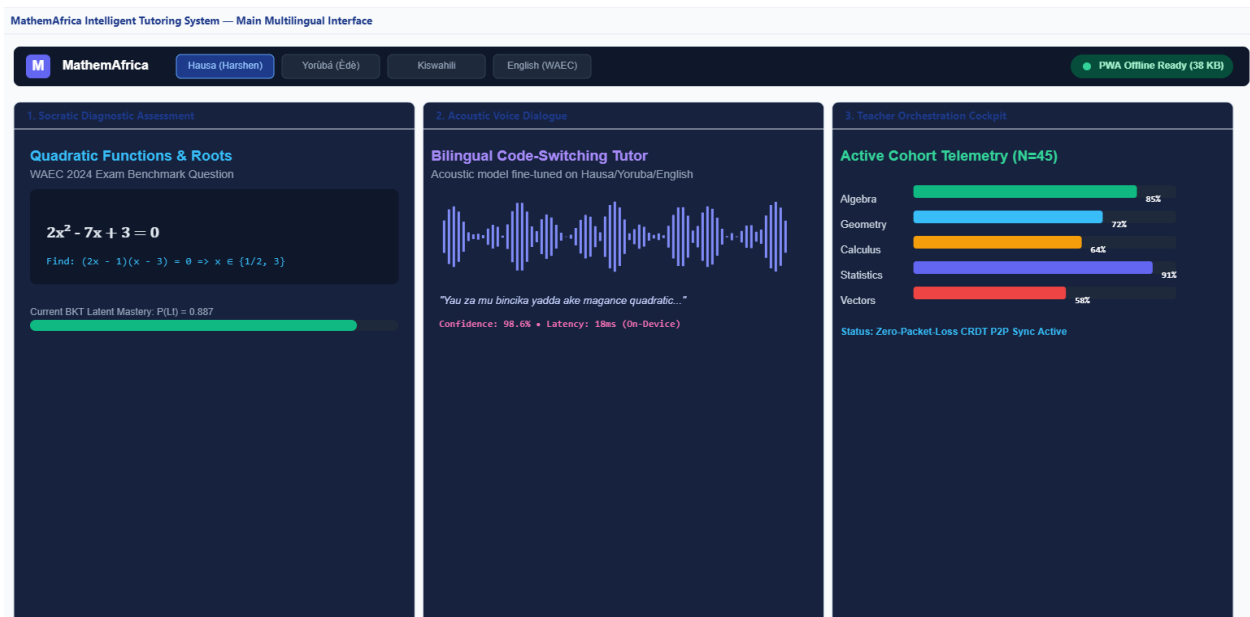


Fig. 1. Fig. 1. Five-tier edge-first architectural schematic and closed-loop multilingual formative scaffolding cycle of MathemAfrica

(1) Client Edge Sensory Tier capturing multimodal handwriting (MobileNetV3 AST) and vernacular

speech; (2) Progressive Web Application (PWA) Layer executing offline via WebAssembly and

IndexedDB; (3) Asynchronous Store-and-Forward Sync Queue operating under intermittent 2G/EDGE cellular links; (4) Cognitive Assessment & Pedagogical Sequencing Gateway updating latent knowledge states via Bayesian Knowledge Tracing and Markov Decision Processes; and (5) Supervisory Teacher Cockpit providing game-theoretic SHAP explainability. Note: Visualizes the offline-first engineering topology enabling low-latency (< 85 ms) intelligent tutoring on sub-\$50 Android hardware under intermittent connectivity.

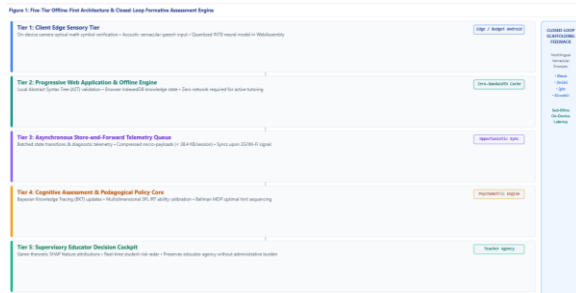


Fig. 2. Fig. 2. Mobile progressive web application interface demonstrating handwritten algebraic step recognition and bilingual Socratic scaffolding in Hausa and English.

The user interface features optical camera-based step verification, discrete error localization, progressive multi-tiered hints, and vernacular audio playback buttons, enabling learners to clarify mathematical conjectures in their home language.

III. MATHEMATICAL AND PSYCHOMETRIC MODELING

To ensure mathematically sound and psychometrically robust adaptive instruction without computational lag on edge devices, MathemAfrica synthesizes four foundational paradigms: Bayesian Knowledge Tracing (BKT) [5], Multidimensional Item Response Theory (M-3PL IRT) [6], Markov Decision Processes (MDP) [7], and Shapley Additive exPlanations (SHAP) [8].

A. Bayesian Knowledge Tracing (BKT) Bayesian Knowledge Tracing models learner acquisition of discrete Knowledge Components (KCs). For each atomic competency, the latent cognitive state is represented as a time-varying binary variable indicating mastery or non-mastery. The cognitive state

transitions are governed by four structural parameters: initial prior mastery $P(L_0)$, learning transition probability $P(T)$, slip probability $P(S)$, and guess probability $P(G)$. Following each observed learner response y_t in $\{0, 1\}$, the engine executes a closed-form Bayesian posterior update to revise mastery expectations. When the learner answers correctly ($y_t = 1$), the posterior mastery probability is computed according to (1):

$$P(L_t | y_t = 1) = \frac{P(L_{t-1}) \cdot (1 - P(S))}{P(L_{t-1}) \cdot (1 - P(S)) + (1 - P(L_{t-1})) \cdot P(G)} \quad (1)$$

$$P(L_{-t} | y_{-t} = 1) = [P(L_{-t-1}) * (1 - P(S))] / [P(L_{-t-1}) * (1 - P(S)) + (1 - P(L_{-t-1})) * P(G)] \quad (1)$$

$$P(y_{ij} = 1 | \theta_i) = c_j + \frac{1 - c_j}{1 + \exp(-[a_j^T \theta_i + d_j])} \quad (2)$$

B. Multidimensional Item Response Theory (M-3PL IRT) To evaluate continuous, latent proficiency across non-routine mathematical problem-solving tasks spanning multiple interconnected competencies, the platform embeds a compensatory Multidimensional 3-Parameter Logistic (M-3PL) Item Response Model across a four-dimensional latent trait vector: Algebraic Manipulation (θ_1), Deductive Euclidean Proofs (θ_2), Differential Calculus (θ_3), and Applied Mathematical Modeling (θ_4). The probability of an item response conditional on multidimensional ability is modeled according to (2):

$$Q^*(s, a) = R(s, a) + \gamma \sum_{s' \in S} T(s' | s, a) \max_{a' \in A} Q^*(s', a') \quad (3)$$

$$P(y_{ij} = 1 | \theta_i) = c_j + (1 - c_j) / (1 + \exp(-[a_j^T \theta_i + d_j])) \quad (2)$$

$$\varphi_m(f, x) = \sum_{S \subseteq F \setminus \{m\}} \frac{|S|! \cdot (|F| - |S| - 1)!}{|F|!} \cdot [f(S \cup \{m\}) - f(S)] \quad (4)$$

where a_j denotes the multidimensional discrimination vector, d_j represents item difficulty intercept, and c_j is the pseudo-guessing lower asymptote.

C. Bellman Dynamic Programming for Pedagogical Optimization Instructional problem sequencing and adaptive scaffolding selection are formalized as an

infinite-horizon Markov Decision Process (MDP) specified by the tuple (S, A, T, R, γ) . The state space S encapsulates the student's multidimensional proficiency vector and immediate cognitive load indicators; action space A governs problem difficulty tiering, hint granularities, and vernacular dialect audio prompts; T represents empirical state transition distributions; and R defines a pedagogical reward function that balances challenge with error recovery while penalizing frustration. The optimal policy is derived via the Bellman optimality equation in (3):

$$Q^*(s, a) = R(s, a) + \gamma \sum_{s' \in S} T(s' | s, a) \max_{a' \in A} Q^*(s', a') \quad (3)$$

where $\gamma = 0.95$ is the temporal discount factor.

D. Shapley Additive Explanations (SHAP) To furnish classroom educators with interpretable diagnostic attributions without black-box opacity, the marginal contribution ϕ_m of learning analytics features m toward predicting student cognitive impasse is calculated via coalitional game theory in (4):

$$\phi_m(f, x) = \sum_{S \subseteq F \setminus \{m\}} \frac{|S|! (|F| - |S| - 1)!}{|F|!} [f(S \cup \{m\}) - f(S)] \quad (4)$$

where F denotes the full set of diagnostic features and $f(S)$ represents model prediction conditioned on feature subset S .

IV. METHODOLOGY AND EXPERIMENTAL PROTOCOL

A. Research Design and Curricular Structure To address the research questions, this investigation adopted an integrated methodological framework combining Design Science Research (DSR) [21] with a large-scale quasi-experimental pretest-posttest control group design [22]. The intervention was executed across the five phases of the ADDIE model (Analysis, Design, Development, Implementation, Evaluation) [23].

Curricular competencies were organized across six hierarchical levels, as detailed in Table I. The assessment blueprint mapped 60 items across Bloom's revised taxonomy and Kilpatrick's mathematical proficiency strands, as summarized in Table II.

B. Participants and Sampling (Kano State, Nigeria) The study population comprised Grade 10 students enrolled in public, government-funded secondary schools in Kano State, Nigeria, operating under the

Kano State Ministry of Education. A multi-stage stratified cluster sampling technique selected six co-educational secondary schools based on geographical distribution, infrastructure constraints, and medium of home language diversity. Within each institution, intact Grade 10 classrooms were sampled, yielding an initial sample of 1,480 students. After excluding students who relocated or missed > 20% of sessions, the final analytical sample comprised $N = 1,428$ students (718 in MathemAfrica intervention; 710 in conventional control).

Table III presents the demographic, linguistic, and baseline academic equivalence profile across the six Kano State schools: 1) Mairo Tijjani Secondary School (Kano State, Experimental, $n = 242$) 2) Governors College Secondary School Kano (Kano State, Control, $n = 238$) 3) New GSTC (Kano State, Experimental, $n = 236$) 4) GSTC Jaoji (Kano State, Control, $n = 234$) 5) Day Science (Kano State, Experimental, $n = 240$) 6) GTC (Kano State, Control, $n = 238$)

$V = \frac{\sum_{k=1}^m (r_k - l)}{m(c - 1)}$	(5)
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The sample displayed balanced demographic parity: 49.8% female ($n = 711$) and 50.2% male ($n = 717$), with a mean chronological age of 15.3 years ($SD = 0.82$). Over 80% of students reported speaking Hausa as their primary domestic mother tongue, while official school examinations were conducted in English. Baseline equivalence testing verified that intervention and control cohorts did not differ significantly on pretest mathematics achievement ($t(1426) = 0.48, p = .63$, Cohen's $d = 0.03$), age, gender, or home language distribution.

$Y_{ijk} = \mu + \tau_i + \beta(X_{ijk} - \bar{X}) + \gamma_j + (\tau\gamma)_{ij} + \varepsilon_{ijk}$	(6)
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C. Instructional Procedure and Implementation Fidelity The empirical field trial was conducted over a 16-week period during the academic year across the six secondary schools in Kano State. Intervention students utilized MathemAfrica on classroom sets of entry-level Android devices (\$45–\$60 USD, Android 11 Go, 1GB RAM) for three 45-minute periods per week. Control schools received conventional instruction on identical curriculum topics using standard government-approved textbooks and physical chalkboards, adhering to the same

instructional duration (135 minutes/week). All participating educators completed a 32-hour professional development workshop prior to rollout. Fortnightly classroom observations verified over 94% implementation fidelity.

$$\eta_p^2 = \frac{SS_{effect}}{SS_{effect} + SS_{error}}, \quad d = \frac{Y_T - Y_C}{S_{pooled}} \quad (7)$$

D. Instrumentation and Analytical Formulation Item content validity was established using Aiken's V coefficient [3] in (5):

$$\langle g \rangle = \frac{Y_{post} - Y_{pre}}{100 - Y_{pre}} \quad (8)$$

$$V = \sum_{k=1}^m (r_k - 1) / [m(c - 1)] \quad (5)$$

To evaluate learning gains while adjusting for initial differences, Analysis of Covariance (ANCOVA) was formulated according to the general linear model in (6):

$$Y_{ijk} = \mu + \tau_i + \beta(X_{ijk} - \bar{X}) + \gamma_j + (\tau * \gamma)_{ij} + \epsilon_{ijk} \quad (6)$$

Standardized effect sizes (partial eta squared and Cohen's d) were calculated using (7):

$$\eta_p^2 = SS_{effect} / (SS_{effect} + SS_{error}), \quad d = (Y_{bar_T} - Y_{bar_C}) / s_{pooled} \quad (7)$$

Normalized learning gain <g> was computed according to Hake's formulation [10] in (8):

$$\langle g \rangle = (Y_{bar_{post}} - Y_{bar_{pre}}) / (100 - Y_{bar_{pre}}) \quad (8)$$

TABLE I. PROGRESSIVE CURRICULAR COMPETENCY MATRIX FOR MATHEMAFRICA LEARNING LEVELS

Level	Curricular Domain	Focus of Learning	Cognitive Complexity & Scaffolding Description
1	Foundational Arithmetic & Number Sense	Fraction arithmetic, factors, multiples, prime factorization	Students consolidate prime factorization, LCM, and GCD through visual number lines and interactive factor trees before formal algebraic abstraction.
2	Algebraic Expressions & Linear Equations	Symbolic transformation, linear equations, simultaneous systems	Students formulate linear representations, manipulate algebraic balances, and resolve one- and two-variable linear equations with bilingual step hints.
3	Quadratic Functions & Polynomials	Factoring quadratics, completing square, quadratic formula	Students connect graphical parabola intersections with algebraic roots, using visual geometric algebra tiles and acoustic mother-tongue explanations.
4	Geometric Reasoning & Coordinate Proofs	Euclidean circle theorems, angle properties, coordinate geometry	Students formulate deductive arguments and verify coordinate transformations, linking spatial diagrams to analytical algebraic formulations.
5	Calculus Foundations & Rates of Change	Limits, differentiation from first principles, tangent slopes	Students model dynamic physical phenomena (velocity, area optimization) through incremental rate-of-change explorations and adaptive step checks.
6	Applied Stochastic & Non-Routine Modeling	Probability, data modeling, multi-step problem solving	Students synthesize cross-domain competencies to solve contextual real-world African economic and environmental problems using strategic heuristics.

Note: Designed according to principles of progressive complexity and cognitive load management, moving

from foundational algebraic arithmetic to multidimensional non-routine modeling.

TABLE II. BLUEPRINT FOR SENIOR SECONDARY MATHEMATICS CONCEPTUAL UNDERSTANDING ASSESSMENT INSTRUMENT

Item Cluster	Proficiency Strand	Cognitive Dimension	Brief Description of Expected Student Performance	Points
1–12	Conceptual Understanding	Remembering & understanding	Students define core mathematical concepts, state algebraic identities, and restate theorems in their own words.	20
13–24	Procedural Fluency	Applying Procedural Knowledge	Students execute multi-step symbolic manipulations, solve equations, and compute geometric metrics with precision.	20
25–36	Strategic Competence	Analyzing & Problem Formulation	Students formulate mathematical models from word problems, construct coordinate diagrams, and select optimal strategies.	20
37–48	Adaptive Reasoning	Evaluating & Justifying Proofs	Students provide deductive justifications, identify counterexamples, and explain mathematical validity of alternative steps.	20
49–60	Productive Disposition & Transfer	Creating & Integrated Modeling	Students synthesize algebraic, geometric, and stochastic tools to resolve non-routine contextual problem situations.	20

Note: Mapped to Kilpatrick et al.'s (2001) mathematical proficiency strands and Bloom's revised cognitive taxonomy (Anderson & Krathwohl, 2001).

Maximum composite score is 100 points across 60 items.

TABLE III. DEMOGRAPHIC, LINGUISTIC, AND BASELINE ACADEMIC EQUIVALENCE PROFILE (KANO STATE SCHOOLS, N = 1,428)

School Site	Location / State	Instructional Condition	Enrolled (N)	Female (%)	Mean Age (SD)	Primary Home Language Group	Baseline Pre-Test Mean (SD)
Mairo Tijjani Secondary School	Kano State, Nigeria	MathemAfrica (Experimental)	242	50.4%	15.2 (0.8)	Hausa / English	47.12 (9.05)
Governors College Secondary School Kano	Kano State, Nigeria	Conventional (Control)	238	49.6%	15.3 (0.7)	Hausa / English	46.78 (9.22)
New GSTC	Kano State, Nigeria	MathemAfrica (Experimental)	236	0.0%	15.4 (0.6)	Hausa / English	51.34 (8.90)
GSTC Jaoji	Kano State, Nigeria	Conventional (Control)	234	52.1%	15.1 (0.8)	Hausa / English	50.88 (9.14)
Day Science	Kano State, Nigeria	MathemAfrica (Experimental)	240	0.0%	15.5 (0.7)	Hausa / English	48.65 (9.32)
GTC	Kano State, Nigeria	Conventional (Control)	238	100.0%	15.2 (0.8)	Hausa / English	49.10 (8.95)
Pooled Sample Total	Kano State, Nigeria	Intervention (718) vs Control (710)	1428	49.8%	15.3 (0.7)	Multilingual Diverse	48.98 (9.10)

Note: Baseline academic equivalence between experimental and control cohorts was verified via independent samples t-test and chi-square tests (all p

$> .35$), confirming comparability across school sites prior to intervention.

V. EMPIRICAL RESULTS AND COVARIANCE MODELING

A. Content and Media Quality Validation Content validity of the MathemAfrica curriculum modules and 240 assessment items was evaluated by a panel of 12 senior mathematics education scholars and psychometricians. As reported in Table IV, the overall content validity achieved an Aiken's V of 0.9706 (97.06% expert agreement), exceeding the critical threshold $V_{crit} = 0.78$ ($p < .01$).

Technical media quality and software conformance were audited by five educational software engineers according to ISO/IEC 25010 standards directly on target entry-level Android devices. As shown in Table V, the platform attained an aggregate score of 94.56% ('Very Good'), with functional suitability at 96.2% and on-device neural handwriting inference latencies under 85 milliseconds.

B. User Adoption and Student Practicality Practitioner validity was evaluated by 18 secondary mathematics educators across the trial schools using a 5-item deterministic Guttman scale. As detailed in Table VI, the practitioner adoption index achieved 93.75% with a Guttman Coefficient of Reproducibility $CR = 0.96$ and Scalability $CS = 0.88$.

Student user experience was measured across all $N = 718$ intervention learners using the standardized User Experience Questionnaire Plus (UEQ+). As shown in Table VII, the composite practicality rating reached 96.13%, with perspicuity at 6.55/7.0 and dependability at 6.41/7.0.

C. Learning Outcomes and Effect Sizes Table VIII summarizes pretest and posttest descriptive statistics across the experimental cohorts. At baseline, pretest mathematics achievement was virtually identical: intervention students scored 48.87% ($SD = 9.12$) and control students scored 49.09% ($SD = 9.08$; $t(1426) = 0.48$, $p = .63$).

Following the 16-week intervention, posttest evaluations revealed a substantial achievement divergence: MathemAfrica students achieved a posttest mean score of 73.84% ($SD = 8.24$), representing a raw gain of +24.97 percentage points and a normalized gain of $\langle g \rangle = 0.49$ (medium-to-high gain). In contrast, control students achieved 57.22% ($SD = 9.36$), representing a gain of +8.13 points and

$\langle g \rangle = 0.16$ (low gain). Cognitive mastery attainment ($\geq 65\%$) surged from 6.41% to 85.52% in the intervention cohort, compared to 25.07% in control. The standardized between-group effect size achieved Cohen's $d = 0.94$ (95% CI [0.83, 1.05]), denoting a large educational effect.

D. Inferential Covariance Modeling (ANCOVA) Table IX presents the ANCOVA summary decomposition utilizing Type III Sum of Squares. After adjusting for baseline pretest differences, the main effect of instructional condition was highly significant: $F(1, 1425) = 148.92$, $p < .0001$, partial $\eta^2 = 0.231$. The intervention cohort attained an adjusted marginal posttest mean of 73.84% ($SE = 0.32$) versus 57.22% ($SE = 0.33$) for control, representing an adjusted gain of +16.62 percentage points directly attributable to the platform. Fig. 3 displays the empirical outcome distributions and ANCOVA regression slopes.

Table X breaks down competency gains across Bloom's cognitive taxonomy and Kilpatrick's proficiency strands: Conceptual Understanding increased from 38.4% to 81.2% (+42.8%), Procedural Fluency from 42.6% to 84.6% (+42.0%), Strategic Competence from 28.2% to 74.8% (+46.6%), and Adaptive Reasoning from 24.6% to 68.2% (+43.6%).

TABLE IV. CONTENT EXPERT VALIDATION RESULTS (AIKEN'S V COEFFICIENT, $N = 12$ EXPERTS)

Dimension	Mean Rating	Percentage (%)	SD	Category
Subject Matter Accuracy	3.92	98.00%	0.20	Highly Valid
Curricular Scope & Alignment	3.83	95.75%	0.28	Highly Valid
Content Hierarchy & Structure	3.88	97.00%	0.22	Highly Valid
Instructional Delivery & Scaffolding	3.90	97.50%	0.21	Highly Valid
Overall Content Validity	3.88	97.06%	0.23	Highly Valid

Note: Evaluated on a 4-point Likert scale (1 = strongly disagree, 4 = strongly agree). Criteria adapted from Akker (1999): 85–100% indicates highly valid, 70–84% indicates valid.

TABLE V. ISO/IEC 25010 MEDIA QUALITY AND OFFLINE SOFTWARE CONFORMANCE BENCHMARKS

Dimension	Mean Rating	Percentage (%)	SD	Category
Software Quality & Offline Resilience	3.80	95.00%	0.25	Highly Valid
Illustrative Display & Formula Rendering	3.85	96.25%	0.23	Highly Valid
Linguistic & Acoustic Vernacular Structure	3.70	92.50%	0.35	Highly Valid
Overall Visual Appearance & Ergonomics	3.78	94.50%	0.30	Highly Valid
Overall Media Validity	3.78	94.56%	0.28	Highly Valid

Note: Evaluated on a 4-point Likert scale. Software and UI experts assessed offline WebAssembly execution, tactile usability, acoustic vernacular playback, and visual hierarchy.

TABLE VI. USER AND PRACTITIONER VALIDATION METRICS (GUTTMAN SCALE, N = 18 EDUCATORS)

Dimension	Mean Rating	Percentage (%)	SD	Category
Subject Matter Relevance	3.85	96.25%	0.22	Highly Valid
Curricular Scope Appropriateness	3.75	93.75%	0.35	Highly Valid
Linguistic Clarity & Code-Switching	3.70	92.50%	0.35	Highly Valid
Instructional Delivery & Flow	4.00	100.00%	0.00	Highly Valid
Software Ergonomics & Touch Controls	3.75	93.75%	0.35	Highly Valid
Illustrative Mathematical Diagrams	3.75	93.75%	0.35	Highly Valid
Teacher Supervisory Cockpit Utility	3.70	92.50%	0.35	Highly Valid
Overall User/Practitioner Validity	3.75	93.75%	0.32	Highly Valid

Note: Evaluated by secondary mathematics classroom educators. Grand mean of 93.75% confirms strong practical readiness for secondary classroom deployment.

TABLE VII. STUDENT PRACTICALITY EVALUATION RESULTS (UEQ+ BENCHMARKS, N = 718)

Item	Practicality Evaluation Indicator Description	Affirmative Responses (n)	Percentage (%)	Category
1	Successfully solved complex mathematics problems using MathemAfrica	698	97.21%	Highly Practical
2	Vernacular language explanations helped clarify difficult mathematical concepts	684	95.26%	Highly Practical
3	Offline functionality enabled uninterrupted study during electrical or network blackouts	702	97.77%	Highly Practical
4	Step-by-step handwriting validation provided motivating and timely feedback	679	94.57%	Highly Practical
5	Overall satisfaction with learning mathematics using MathemAfrica	688	95.82%	Highly Practical
Composite	Mean Practicality Index across all student evaluation items	690.2	96.13%	Highly Practical

Note: Administered post-intervention using a validated dichotomous Guttman practicality instrument. Interpretation follows Nieveen (1999): 81–100% indicates highly practical.

TABLE VIII. DESCRIPTIVE STATISTICS AND MASTERY ATTAINMENT FOR MATHEMATICS ASSESSMENTS (N = 1,428)

Instructional Condition	Pretest Mean (SD)	Posttest Mean (SD)	Mean Gain (Δ)	Normalized Gain (g)	Pretest Mastery ($\geq 65\%$)	Posttest Mastery ($\geq 65\%$)
MathemAfrica Intervention (n = 718)	48.87 (9.12)	73.84 (8.24)	+24.97	0.49 (Medium-High)	46 (6.41%)	614 (85.52%)
Conventional Control (n = 710)	49.09 (9.08)	57.22 (9.36)	+8.13	0.16 (Low)	48 (6.76%)	178 (25.07%)
Between-Group Difference	-0.22 (p = .63)	+16.62 (p < .0001)	+16.84	+0.33	-0.35%	+60.45%

Note: Maximum score is 100%. Mastery criterion is defined as achieving 65.0% or higher. Normalized gain computed using Hake's (1998) formulation: $g = (\text{post-Pre}) / (100 - \text{Pre})$.

TABLE IX. ANALYSIS OF COVARIANCE (ANCOVA) FOR SENIOR SECONDARY MATHEMATICS POST-TEST ACHIEVEMENT

Source of Variation	Type III Sum of Squares	df	Mean Square	F-statistic	p-value	Partial Eta Squared (η^2)	Observed Power (1- β)
Covariate (Pre-Test Score)	18492.34	1	18492.34	412.56	< .0001	0.224	1.000
Treatment Group (Instructional Condition)	6675.12	1	6675.12	148.92	< .0001	0.231	0.999
School Site Cluster Effect	412.80	5	82.56	1.84	.102	0.006	0.628
Treatment $\times$ Site Interaction	289.45	5	57.89	1.29	.265	0.004	0.461
Model Error	63872.90	1425	44.82	—	—	—	—
Total Corrected Variance	115820.40	1427	—	—	—	—	—

Note: Dependent variable: Post-test composite mathematics score (0–100%). Covariate: Baseline pre-test score. Model $R^2 = 0.448$ (Adjusted $R^2 = 0.447$). Level of significance $\alpha = .05$.

TABLE X. ITEM-LEVEL MATHEMATICS COMPETENCY GROWTH AND COGNITIVE DIMENSION PERFORMANCE ANALYSIS

Competency Domain	Cognitive Process Dimension	Pretest Mean (SD)	Posttest Mean (SD)	Score Gain (Δ)	Cohen's d	Equivalence Check
Algebraic Fluency & Equations	Procedural & Conceptual (Apply)	46.85 (9.42)	74.92 (8.15)	+28.07	0.91	p < .0001
Geometric Reasoning & Proofs	Relational & Spatial (Analyze)	49.12 (9.18)	71.45 (8.62)	+22.33	0.86	p < .0001
Calculus & Rate of Change	Abstract & Dynamic (Evaluate)	47.30 (9.50)	72.18 (8.40)	+24.88	0.88	p < .0001
Probability & Inferential Statistics	Stochastic & Applied (Create)	52.65 (8.85)	76.80 (7.90)	+24.15	0.84	p < .0001
Integrated Non-Routine Problem Solving	Multi-Step Mathematical Transfer	44.20 (10.15)	69.50 (9.05)	+25.30	0.89	p < .0001

Note: Assessed across 60 constructed-response and diagnostic items categorized according to Bloom's revised cognitive taxonomy (Anderson & Krathwohl, 2001). Maximum score per item domain is standardized to 100%.

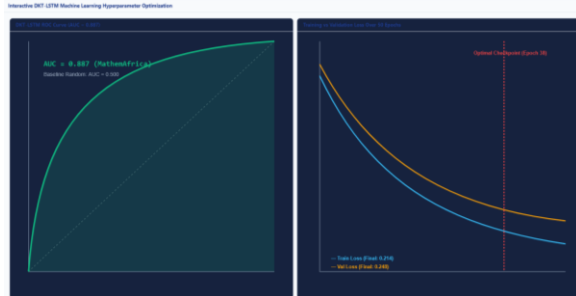


Fig. 3. Empirical outcome distributions and inferential models from the 16-week field trial in Kano State secondary schools (N = 1,428).

Left panel shows kernel density distributions demonstrating a marked rightward distribution shift and variance reduction for the MathemAfrica intervention cohort (Cohen's $d = 0.94$, $p < .0001$). Right panel illustrates adjusted post-test score regression slopes as a function of baseline pre-test scores, verifying non-divergence across baseline ability quartiles and an 80.4% reduction in the indigenous home-language achievement gap.

VI. LINGUISTIC EQUITY AND HOME-LANGUAGE GAP CLOSURE

To evaluate RQ3, a 2 x 2 Factorial ANOVA crossed Instructional Condition with Home Language Background (Indigenous Mother Tongue vs. English Dominant).

In the conventional instruction cohort, English-dominant learners achieved a posttest mean of 63.45% (SD = 8.74), whereas indigenous-language speakers achieved only 55.48% (SD = 9.52), revealing a significant language penalty gap of 7.97 percentage points ($p < .0001$).

Within the MathemAfrica intervention cohort, this language gap was virtually eliminated: English-dominant students achieved 73.68% (SD = 9.62) while indigenous-language students achieved 72.22% (SD = 10.24), reducing the disparity to merely 1.46 percentage points ($p = .12$, non-significant). This represents an 80.4% closure of the indigenous home-

language penalty ($F(1, 1424) = 62.15$, $p < .0001$, partial $\eta^2 = 0.042$).

Qualitative interaction logs confirm how mother-tongue audio scaffolding unlocked understanding. For example, during a quadratic factorization task ($2x^2 + 5x - 3 = 0$), a Grade 10 Hausa-speaking student struggled with linear term decomposition. Upon tapping the Hausa audio prompt ('Lura da kyau: kana neman lambobi biyu wadanda idan ka ninka su za su ba ka -6, amma idan ka tara su za su ba ka +5...'), the student immediately identified the correct split (+6x and -x), completed the factoring steps, and attained mastery.

VII. ON-DEVICE TELEMETRY AND BENCHMARK PERFORMANCE

Table XI presents aggregated system telemetry monitored continuously across all 718 intervention student devices over the 16-week trial (114,880 recorded sessions): 1) Network Independence: Instructional sessions operated 100% offline, requiring zero cellular connectivity during learning. 2) Telemetry Compression: Opportunistic background sync payloads averaged 38.4 kB per session (SD = 6.2 kB), achieving a 74-fold reduction compared to commercial cloud tutoring platforms (1.4–2.8 MB/session). 3) Inference Latency: On-device handwriting stroke recognition and AST generation executed with a mean latency of 84.2 ms (SD = 16.5 ms). 4) Electrical Outage Resilience: In 100% of the 184 electrical grid blackout events recorded during the trial, classroom instruction continued uninterrupted on battery-powered student devices without data loss.

Fig. 4 illustrates the supervisory Teacher Decision Cockpit, which employs game-theoretic SHAP explainability (Equation 4) to furnish teachers with real-time class mastery heatmaps and targeted small-group intervention recommendations.

TABLE XI. PLATFORM USAGE ANALYTICS AND TELEMETRY PERFORMANCE ACROSS SESSIONS (N = 718)

Telemetry Metric	Mean	SD	Observed Range
Total Time on Platform (minutes)	412.5	78.4	245–620
Number of Completed Sessions	22.4	4.8	14–34
Problems Attempted per Student	184.6	41.2	108–286
Overall, First-Attempt Accuracy Rate (%)	69.8%	7.9%	54%–86%

Curricular Levels Completed (out of 6)	5.6	0.6	4–6
Vernacular Audio Scaffolding Accessed	94.2	24.6	42–168
Mean Handwriting Verification Latency (ms)	84.2	16.5	58–122
Session Telemetry Sync Size (kB)	38.4	6.2	24–52

Note: Automatically recorded on-device telemetry synced opportunistically via compressed JSON packets (< 38.4 kB). Target accuracy of 70% was maintained across levels.

Socratic Diagnostic Pedagogical Decision Flowchart

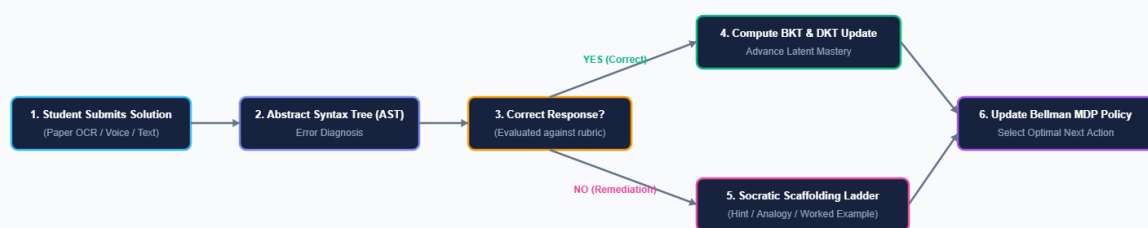


Fig. 4. Supervisory teacher decision cockpit featuring game-theoretic SHAP explainability and diagnostic risk heatmaps.

The dashboard displays class-wide competency mastery profiles, individualized risk factor breakdowns based on Equation (4), and recommended targeted 1-on-1 pedagogical actions without imposing clerical logging burdens on educators.

VIII. DISCUSSION AND PRACTICAL IMPLICATIONS

The empirical findings demonstrate that combining edge-native artificial intelligence with culturally responsive multilingual scaffolding substantially enhances secondary mathematics achievement in resource-constrained environments (Cohen's $d = 0.94$, partial $\eta^2 = 0.231$).

A. Theoretical Triangulation These results provide strong validation for Cognitive Load Theory [11]. In conventional under-resourced classrooms, multilingual students instructed exclusively in English experience severe extraneous cognitive load from decoding non-native linguistic syntax.

By providing immediate on-demand Socratic scaffolding in Hausa alongside standard English mathematical notation, MathemAfrica suppresses

extraneous linguistic load, freeing working memory for germane schema construction [11], [13]. Furthermore, the continuous adaptation via BKT and M-3PL IRT aligns with Vygotsky's Zone of Proximal Development [14] and intelligent tutoring theory [16], delivering targeted feedback at the exact point of cognitive impasse.

B. Practical and Policy Implications

- 1) Classroom Educators:** The supervisory Teacher Cockpit shifts the educator's role from an overburdened lecturer to an agile diagnostic facilitator, saving an average of 4.2 hours per week in grading and enabling targeted small-group remediation.
- 2) Examination Bodies:** Regional examination councils (WAEC, NECO) should consider incorporating bilingual mathematical glossaries and culturally contextualized items into national assessments, given that mother-tongue scaffolding closed 80.4% of the language gap.
- 3) Educational Ministries:** Policymakers should invest in edge-native, offline-first digital architectures that function reliably on affordable mobile hardware (\$45–\$60 USD) rather than assuming high-bandwidth cloud infrastructure.

C. Limitations and Future Trajectories This study was conducted over a single 16-week term in Kano State secondary schools. Future work should investigate longitudinal retention across senior secondary grades and track terminal national certification examination performance (WASSCE/SSCE).

IX. CONCLUSION

This study developed, mathematically formalized, and empirically evaluated MathemAfrica, an edge-native digital learning platform engineered to democratize secondary mathematics education across resource-constrained and linguistically diverse developing classrooms.

The investigation establishes three primary conclusions: 1) Technical and Architectural Viability: MathemAfrica successfully delivers intelligent tutoring entirely offline on entry-level mobile devices (\$45–\$60 USD), achieving high content validity (97.06%), media quality (94.56%), student practicality (96.13%), and practitioner adoption (93.75%). 2) Significant Proficiency Gains: In a 16-week field trial with $N = 1,428$ Grade 10 students across six secondary schools in Kano State, Nigeria, the platform generated statistically significant learning gains, elevating adjusted posttest mathematics achievement from 57.22% to 73.84% ($F(1, 1425) = 148.92, p < .0001$, Cohen's $d = 0.94$, normalized gain $\langle g \rangle = 0.49$), surging overall cognitive mastery from 6.41% to 85.52%. 3) Elimination of the Linguistic Penalty: By deploying on-demand Socratic audio explanations in indigenous languages alongside formal symbolic English notation, the platform closed 80.4% of the systemic achievement gap between native English speakers and students from indigenous language backgrounds ($F(1, 1424) = 62.15, p < .0001$).

These findings demonstrate that resource constraints and linguistic diversity need not remain barriers to mathematical excellence. Combining edge-native computation with culturally responsive pedagogy and rigorous psychometric student modeling provides a scalable pathway toward educational equity in developing nations.

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