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Research Paper

Development of Low-Cost Chemistry Lab Kits for Resource-Limited Settings

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Abstract
The inadequacy of chemistry laboratory facilities in resource-limited educational settings poses a significant barrier to effective science education and compromises the development of practical skills essential for scientific literacy. This study addresses this challenge through the systematic development and validation of low-cost chemistry laboratory kits designed specifically for secondary schools and teacher education institutions in Nigeria and similar resource-constrained contexts. Employing a Research and Development (R&D) methodology guided by the ADDIE (Analysis, Design, Development, Implementation, and Evaluation) instructional design framework, we developed portable, affordable chemistry kits covering fundamental topics including acid-base reactions, electrochemistry, qualitative analysis, and separation techniques. The kits utilize locally-sourced materials, simple electronic components (Arduino-based sensors), and everyday items adapted for scientific experimentation, reducing costs by approximately 75% compared to commercial laboratory equipment while maintaining pedagogical effectiveness. A quasi-experimental study involving 240 senior secondary school students across six schools in Kwara State evaluated the kits' impact on students' practical skills, conceptual understanding, and attitudes toward chemistry. Results demonstrated significant improvements in all three domains: practical skills increased by 68% (Cohen's d = 1.84), conceptual understanding improved by 52% (Cohen's d = 1.45), and positive attitudes toward chemistry increased by 43% (Cohen's d = 1.12), all statistically significant at $p < 0.001$. Qualitative feedback from 30 chemistry teachers indicated high levels of satisfaction with the kits' usability, pedagogical appropriateness, and potential for replication. This study contributes a validated framework for low-cost laboratory development, detailed kit specifications and construction protocols, and empirical evidence of educational effectiveness. The findings have important implications for chemistry education policy, teacher preparation programs, and strategies for achieving Sustainable Development Goal 4 (quality education) in resource-limited contexts.

Keywords: *Low-cost laboratory, chemistry education, hands-on learning, resource-limited settings, practical skills development, instructional materials, Nigeria*

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I. Introduction

Chemistry education plays a fundamental role in developing scientific literacy, critical thinking skills, and problem-solving abilities essential for participation in knowledge-based economies (Hofstein & Lunetta, 2004). Central to effective chemistry education is practical laboratory work, which enables students to observe phenomena, verify theoretical concepts, develop manipulative skills, and engage in authentic scientific inquiry (Johnstone & Al-Shuaili, 2001). The importance of laboratory experiences is recognized globally, with most chemistry curricula mandating substantial practical components (National Research Council, 2012). However, a persistent challenge in developing countries, including Nigeria, is the inadequacy of laboratory facilities and equipment that severely constrains students' opportunities for hands-on learning (Hofstein & Mamlok-Naaman, 2007).

1.1 The Laboratory Equipment Crisis in Nigerian Chemistry Education

Nigerian secondary schools and teacher education institutions face acute shortages of chemistry laboratory equipment and materials (Okebukola, 2019). A national survey by the Nigerian Educational Research and Development Council (NERDC) found that fewer than 30% of secondary schools have functional chemistry laboratories meeting minimum standards, with rural schools particularly disadvantaged (Federal Ministry of Education, 2018). This inadequacy stems from multiple factors:

Financial Constraints: Commercial laboratory equipment is prohibitively expensive for most schools. A standard chemistry laboratory setup for a class of 40 students can cost upwards of ₦5,000,000 (approximately $12,000 USD), far exceeding annual science budgets in most schools (Olibie & Akudolu, 2013). Recurring costs for consumables, reagents, and equipment maintenance compound the financial burden.

Procurement Challenges: Imported laboratory equipment faces customs delays, high shipping costs, and complex procurement procedures. Local suppliers often stock limited ranges of equipment, and quality can be inconsistent. Schools in remote areas face additional logistical challenges accessing suppliers concentrated in major cities.

Infrastructure Limitations: Beyond equipment costs, many schools lack appropriate physical infrastructure for laboratories, including adequate electrical supply, water, ventilation, and storage facilities. The cost of establishing complete laboratory infrastructure deters investment in equipment.

Limited Technical Support: Commercial equipment often requires specialized maintenance and repair services unavailable in many locations. When equipment breaks, replacement parts are difficult to obtain, rendering expensive investments useless.

Mismatch with Curriculum Needs: Some commercially available equipment designed for industrial or research applications proves inappropriate for secondary school curricula, either being unnecessarily sophisticated or not addressing specific learning objectives.

The consequences of inadequate laboratory facilities are profound. Students graduate with theoretical knowledge but limited practical skills, undermining their preparation for higher education and careers in science, technology, engineering, and mathematics (STEM) fields (Ofozoba & Ofozoba, 2024). Teachers resort to demonstration-only methods or omit practical work entirely, reducing chemistry to abstract memorization rather than empirical investigation. This contributes to students' negative attitudes toward chemistry and poor performance in national examinations (West African Examinations Council, 2020).

1.2 Low-Cost Laboratories as a Solution

Low-cost laboratories—defined as practical learning facilities developed using affordable, locally-available materials that substantially reduce costs while maintaining educational effectiveness—offer a promising solution to equipment inadequacy (Fajrin & Hakim, 2022). The concept encompasses several approaches:

Locally-Sourced Materials: Using everyday items (bottles, containers, household chemicals) and locally-available materials rather than specialized laboratory apparatus. For example, plastic bottles can serve as gas collection vessels, kitchen vinegar as an acid source, and baking soda as a base.

Simplified Equipment: Developing simplified versions of standard apparatus that retain essential functionality while eliminating non-essential features. An example is using a simple battery-powered stirrer rather than an expensive magnetic stirrer.

Microchemistry Techniques: Reducing reagent quantities and apparatus scale, which decreases costs, improves safety, and minimizes waste. Microchemistry allows more students to conduct individual experiments with limited resources.

Do-It-Yourself (DIY) Construction: Enabling teachers and students to construct apparatus from readily available materials and simple tools, fostering creativity and deeper understanding of equipment function.

Open-Source Electronics: Utilizing affordable platforms like Arduino and Raspberry Pi to create low-cost sensors, controllers, and data acquisition systems that previously required expensive commercial equipment (Ekin et al., 2021).

Portable and Modular Designs: Creating compact, portable kits that can be easily transported, stored, and used in classrooms lacking dedicated laboratory spaces.

Global experience demonstrates that low-cost approaches can maintain pedagogical quality while dramatically reducing costs. Studies from various developing countries show cost reductions of 70-90% compared to commercial equipment, with comparable or superior learning outcomes (Prieto et al., 2017). The COVID-19 pandemic accelerated interest in portable, low-cost kits that students could use at home during school closures, further demonstrating the versatility of this approach (Bekasiewicz et al., 2021).

1.3 The Nigerian Context: Opportunities and Challenges

Nigeria's specific context presents both opportunities and challenges for low-cost laboratory development:

Opportunities:

- Large, growing student population creating substantial demand for affordable laboratory solutions
- National Curriculum and minimum standards providing clear learning objectives and quality benchmarks
- Rich tradition of informal sector innovation and local fabrication providing technical skills base

- Government policy emphasis on science education and STEM development creating supportive policy environment
- Expanding teacher education infrastructure offering platforms for capacity building
- Availability of many basic materials and chemicals in local markets

Challenges:

- Quality assurance concerns about locally-developed equipment meeting safety and educational standards
- Limited experience among teachers in constructing and utilizing improvised apparatus
- Potential resistance from stakeholders viewing low-cost equipment as inferior "make-do" solutions rather than legitimate pedagogical innovations
- Need for comprehensive teacher training and ongoing support for effective implementation
- Ensuring durability and safety of locally-constructed equipment
- Achieving standardization while allowing for local adaptation and creativity

1.4 Research Gap and Objectives

While the concept of low-cost laboratories is not new, systematic research on their development, validation, and implementation in Nigerian chemistry education remains limited. Existing literature predominantly focuses on developed countries or provides anecdotal rather than empirical evidence of effectiveness. Specific gaps include:

1. Lack of Contextualized Design Frameworks: Most low-cost laboratory literature draws on Western contexts; frameworks explicitly addressing Nigerian curriculum requirements, material availability, and cultural contexts are scarce.
2. Limited Empirical Validation: Few studies rigorously evaluate low-cost chemistry kits' educational impacts using experimental or quasi-experimental designs with validated outcome measures.
3. Insufficient Implementation Guidance: While some studies describe individual apparatus, comprehensive kits with detailed construction protocols, implementation guidelines, and teacher support materials are rare.
4. Narrow Scope: Most research focuses on specific topics (e.g., acid-base titration) rather than comprehensive kit systems addressing multiple curriculum areas.
5. Neglect of Teacher Perspectives: Limited research examines teachers' experiences implementing low-cost laboratories, identifying implementation challenges, or documenting necessary support structures.
6. Inadequate Cost-Effectiveness Analysis: Few studies provide detailed cost comparisons or examine total cost of ownership including maintenance and consumables.

This study addresses these gaps by:

Objective 1: Developing a comprehensive framework for low-cost chemistry laboratory kit design contextualized to Nigerian secondary education curriculum and resource constraints.

Objective 2: Designing and constructing low-cost chemistry kits covering major curriculum topics using locally-sourced materials and simple construction techniques.

Objective 3: Empirically evaluating the kits' educational effectiveness through a quasi-experimental study measuring impacts on students' practical skills, conceptual understanding, and attitudes toward chemistry.

Objective 4: Documenting teachers' perspectives on the kits' usability, pedagogical appropriateness, implementation challenges, and support needs.

Objective 5: Conducting cost-effectiveness analysis comparing low-cost kits to commercial equipment alternatives.

Objective 6: Developing comprehensive implementation resources including construction manuals, teacher guides, and student activity sheets.

1.5 Significance of the Study

This research makes several important contributions:

Theoretical Contributions:

- Extends low-cost laboratory literature to sub-Saharan African contexts
- Develops and validates a design framework for contextualized laboratory kit development
- Contributes to understanding of relationships between hands-on practical work, conceptual learning, and affective outcomes in resource-limited settings

Practical Contributions:

- Provides validated, replicable low-cost chemistry kits directly usable in Nigerian schools
- Offers detailed construction protocols enabling teachers and students to fabricate equipment
- Generates comprehensive implementation resources supporting effective classroom use
- Demonstrates cost-effective alternatives to expensive commercial equipment

Policy Contributions:

- Provides evidence-based recommendations for chemistry education policy and resource allocation

- Informs teacher education curriculum regarding practical skills and improvisation
- Supports strategies for achieving Sustainable Development Goal 4 (quality education)
- Contributes to discussions of sustainable, contextually-appropriate educational technology

1.6 Structure of the Manuscript
The remainder of this manuscript is organized as follows: Section 2 reviews relevant literature on laboratory learning, low-cost equipment development, and chemistry education in resource-limited settings. Section 3 describes the research methodology including kit development framework, experimental design, instruments, and analysis procedures. Section 4 presents results addressing each research objective. Section 5 discusses findings in relation to existing literature, theoretical implications, practical applications, and limitations. Section 6 concludes with recommendations for policy, practice, and future research.

II. Literature Review

2.1 Theoretical Foundations of Laboratory Learning in Chemistry Education
2.1.1 Constructivist Learning Theory

Laboratory work in chemistry education is fundamentally grounded in constructivist epistemology, which posits that learners actively construct knowledge through interaction with their environment rather than passively receiving information (Driver et al., 1994). Piaget's cognitive constructivism emphasizes that learners develop understanding by manipulating objects and observing outcomes, accommodating new experiences into existing cognitive schemas or modifying those schemas when confronted with anomalies (Piaget, 1970). Chemistry laboratory work provides rich opportunities for such cognitive engagement: students formulate hypotheses, design experiments, observe phenomena, interpret results, and reconcile findings with theoretical frameworks.

Vygotsky's social constructivism adds the crucial dimension of social interaction, arguing that learning occurs through collaborative dialogue and scaffolded support from more knowledgeable others (Vygotsky, 1978). In laboratory contexts, students co-construct understanding through peer discussion, collaborative problem-solving, and teacher guidance. The Zone of Proximal Development (ZPD) concept is particularly relevant: laboratory activities should challenge students beyond their independent capability while remaining achievable with appropriate support. Well-designed low-cost laboratory kits can provide such scaffolding through simplified procedures, visual cues, and structured activity sheets.

2.1.2 Experiential Learning Theory

Kolb's (1984) Experiential Learning Theory provides another important theoretical lens. The theory proposes that effective learning involves a four-stage cycle: concrete experience (doing/experiencing), reflective observation (reviewing/reflecting on experience), abstract conceptualization (concluding/learning from experience), and active experimentation (planning/trying what was learned). Laboratory work naturally facilitates this cycle: students conduct experiments (concrete experience), observe and record results (reflective observation), interpret findings in light of theoretical frameworks (abstract conceptualization), and apply learning to new situations or design new experiments (active experimentation).

The "learning by doing" principle central to experiential learning theory aligns with research showing that active engagement with materials enhances retention and understanding. Dale's (1969) Cone of Experience suggests that students retain approximately 10% of what they read, 20% of what they hear, but 70% of what they do. While these specific percentages are contested, the underlying principle that active engagement enhances learning is well-supported (Khaing et al., 2018). Chemistry laboratory work provides precisely such active engagement, making theoretical concepts tangible and memorable.

2.1.3 Situated Cognition and Authentic Learning

Situated cognition theory argues that knowledge is inherently contextual, developed through authentic activities in realistic contexts (Brown et al., 1989). From this perspective, laboratory work provides authentic scientific practice—students engage in genuine scientific inquiry, not merely applying pre-determined procedures to reach known outcomes. Well-designed laboratory experiences should mirror authentic scientific work: formulating questions, designing investigations, troubleshooting problems, interpreting ambiguous data, and communicating findings. Low-cost laboratory kits can enhance authenticity by requiring students to improvise, adapt procedures to available materials, and creatively solve problems—activities that mirror real-world scientific practice more closely than following rigid protocols with perfect apparatus (Hofstein & Lunetta, 2004). When students construct apparatus or adapt household materials for scientific purposes, they develop deeper understanding of equipment function and broader problem-solving capabilities.

2.2 Purposes and Outcomes of Chemistry Laboratory Work

Research identifies multiple purposes and intended outcomes for chemistry laboratory education (Hofstein & Lunetta, 2004; Johnstone & Al-Shuaili, 2001):

Cognitive Outcomes:

- Verification and consolidation of theoretical concepts through empirical observation
- Development of scientific reasoning and inquiry skills
- Understanding of scientific methodology and processes
- Ability to interpret data and draw evidence-based conclusions
- Development of problem-solving skills and troubleshooting capabilities
- Understanding relationships between macroscopic observations, submicroscopic processes, and symbolic representations—Johnstone's (1991) "triangle" of chemistry learning

Procedural/Psychomotor Outcomes:

- Mastery of laboratory techniques and manipulative skills
- Ability to use apparatus and instruments safely and effectively
- Development of observation and measurement skills
- Understanding of experimental design and control of variables
- Data collection, recording, and analysis capabilities

Affective Outcomes:

- Positive attitudes toward science and scientific inquiry
- Increased interest in and appreciation for chemistry
- Development of scientific habits of mind including curiosity, skepticism, precision, and persistence
- Confidence in conducting scientific investigations
- Appreciation for safety and ethical considerations in scientific work

Social Outcomes:

- Collaborative skills through group laboratory work
- Scientific communication abilities (oral and written)
- Ability to give and receive constructive feedback
- Development of leadership and teamwork capabilities

Effective laboratory experiences should address multiple outcome dimensions simultaneously. However, research indicates that traditional "cookbook" laboratory exercises—where students follow rigid protocols to reach predetermined results—often fail to achieve many intended outcomes, particularly higher-order cognitive skills and authentic understanding of scientific inquiry (Domin, 1999). This suggests the need for more open-ended, inquiry-oriented laboratory experiences, which low-cost kits can facilitate by requiring adaptation and problem-solving.

2.3 Challenges in Laboratory Education in Developing Countries

While the importance of laboratory work is widely recognized, implementation in developing countries faces numerous obstacles documented in research literature:

Resource Constraints: Multiple studies document inadequate laboratory facilities, equipment, and consumables in developing country schools (Lunetta et al., 2007). Hofstein and Mamlok-Naaman (2007) found that African and Asian schools particularly struggle with equipment shortages, with some schools having no functional laboratories at all. This aligns with Nigerian data showing fewer than 30% of schools meeting minimum laboratory standards (Federal Ministry of Education, 2018).

Infrastructure Limitations: Beyond equipment, many schools lack basic infrastructure—reliable electricity, water supply, storage facilities, and appropriate physical spaces—necessary for laboratory work (Okebukola, 2019). Safety equipment like fume hoods, emergency showers, and fire extinguishers are often absent, creating safety concerns that lead administrators to restrict laboratory access.

Large Class Sizes: Developing country schools often have student-teacher ratios exceeding 1:40, making individual hands-on laboratory work difficult even when equipment exists (Olibie & Akudolu, 2013). Equipment shortages exacerbate this: when only one apparatus exists for 40 students, practical work becomes teacher demonstration rather than student investigation (Berman et al., 2021).

Limited Teacher Preparation: Many chemistry teachers lack adequate preparation in practical skills, laboratory management, and safety procedures (Ofozoba & Ofozoba, 2024). Preservice training often emphasizes theoretical content over practical pedagogy. When teachers themselves lack confidence in laboratory work, they avoid it or implement it poorly.

Curriculum and Assessment Pressures: Despite curriculum requirements for practical work, assessment systems often emphasize theoretical knowledge through written examinations, creating incentives to prioritize lecture over laboratory time (West African Examinations Council, 2020). Teachers facing pressure for examination success may view laboratory work as "nice but non-essential."

Safety Concerns: Legitimate safety concerns about hazardous chemicals, gas supplies, and student safety in poorly-equipped laboratories cause some administrators to restrict laboratory access. Lack of safety equipment and training compounds these concerns.

Maintenance and Sustainability: Equipment that breaks cannot be repaired due to lack of technical expertise or spare parts. Consumables run out and cannot be replaced due to budget constraints or procurement difficulties. This creates cycles of underutilization and deterioration.

2.4 Low-Cost Laboratory Approaches: Global Evidence

Research from various contexts demonstrates that low-cost approaches can address resource constraints while maintaining educational quality:

2.4.1 Microchemistry Approaches

Microchemistry—conducting experiments at reduced scale using smaller quantities of reagents and miniaturized apparatus—offers multiple advantages documented in research:

Cost Reduction: Studies show 50-80% reduction in reagent costs through microchemistry (Bradley, 2001). Smaller quantities also reduce storage and disposal costs.

Safety Enhancement: Reduced chemical quantities decrease exposure risks and accident consequences. This is particularly important in settings lacking sophisticated safety equipment.

Environmental Benefits: Less chemical waste aligns with green chemistry principles and reduces environmental impact (Singh et al., 2017).

Pedagogical Advantages: Smaller scales allow more students to conduct individual experiments with limited resources. Some studies suggest that the precision and care required in microchemistry enhances students' manipulative skills.

Research validating microchemistry's educational effectiveness includes comparative studies showing equivalent or superior learning outcomes compared to conventional scale (Bradley, 2001). However, implementation challenges include the need for specialized micropipettes and small-scale glassware, which can be costly if purchased commercially.

2.4.2 Locally-Sourced and Improvised Equipment

Numerous studies document successful use of locally-available materials as laboratory apparatus:

Prieto et al. (2017) developed low-cost cell migration assays using fish scales and household materials, demonstrating high educational effectiveness in biology courses. Firdaus et al. (2019) created spectrophotometers using smartphone cameras and cardboard, achieving results comparable to commercial instruments at fraction of the cost. Berman et al. (2021) developed portable air conditioning training kits using commonly available materials, significantly improving students' practical understanding.

Nigerian-specific examples include improvised apparatus for distillation using plastic bottles and tubing (Adekunle, 2017), homemade indicators from plants like hibiscus and beetroot (Ogunniyi et al., 2014), and simple electrochemistry cells using graphite from pencils and household chemicals (Akpan, 2016). These studies demonstrate both feasibility and educational effectiveness.

Success factors identified include:

- Careful selection ensuring improvised materials reliably demonstrate intended concepts
- Clear instructions and visual guides supporting construction and use
- Teacher training in improvisation techniques
- Quality assurance mechanisms ensuring safety and functionality

2.4.3 Open-Source Electronics and Sensors

The availability of affordable microcontrollers (Arduino, Raspberry Pi) and sensors has enabled creation of low-cost electronic laboratory instruments:

Ekin et al. (2021) developed DIY light-wave sensing and communication projects using Arduino and common components, achieving significant learning outcomes in engineering courses. Uyanik and Catalbas (2018) created feedback control systems using Arduino-Simulink interfaces, providing hands-on experience previously requiring expensive commercial systems. Khaing et al. (2018) developed logic gate training kits using Arduino, improving understanding of digital circuits.

In chemistry education specifically, Arduino-based systems have been developed for:

- pH measurement using inexpensive sensors
- Temperature control for experiments requiring precise heating
- Automated titration systems
- Colorimetry and spectrophotometry
- Data logging for kinetics experiments

Studies consistently show high student engagement with these systems, development of both chemistry and basic electronics skills, and substantial cost savings (typically 80-90% reduction) compared to commercial equivalents (Fajrin & Hakim, 2022).

2.4.4 Virtual and Remote Laboratories

Virtual laboratories—computer simulations of experiments—and remote laboratories—web-based interfaces allowing students to control physical apparatus remotely—represent another low-cost approach:
Bima et al. (2021) found virtual laboratories effectively supported practical learning in Indonesian vocational schools lacking physical facilities. Slamnik-Kriještorac et al. (2021) compared cloud-based virtual labs to low-cost physical labs, finding engineering students valued hands-on experience but recognized virtual alternatives' value when physical access is limited. During COVID-19 school closures, virtual and remote laboratories enabled continuation of practical learning (Bekasiewicz et al., 2021). However, research indicates virtual approaches, while valuable, cannot fully replace hands-on manipulation for developing practical skills and embodied understanding (Wong et al., 2020). For chemistry education, virtual labs effectively teach concepts and procedures but may not develop manipulative skills or authentic understanding of chemical behavior. Optimal approaches combine virtual simulation with some hands-on experience, potentially using portable low-cost kits students can use at home.

2.5 Design Frameworks for Low-Cost Laboratories

While substantial research demonstrates low-cost approaches' feasibility and effectiveness, systematic frameworks for designing and implementing low-cost laboratory systems are less developed. Fajrin and Hakim (2022) conducted a systematic review identifying common approaches but noted the absence of comprehensive design frameworks.

2.5.1 General Principles from Educational Technology Design

Instructional design frameworks like ADDIE (Analysis, Design, Development, Implementation, Evaluation) provide general guidance (Branch, 2009):
Analysis: Identifying learner needs, curriculum requirements, resource constraints, and context-specific factors
Design: Specifying learning objectives, assessment strategies, instructional activities, and materials requirements
Development: Creating materials, apparatus, and supporting resources
Implementation: Deploying materials in educational contexts with appropriate teacher preparation and student orientation
Evaluation: Assessing effectiveness and iterating based on feedback
While useful, such frameworks require adaptation for low-cost laboratory development's unique challenges, including material sourcing, construction protocols, safety validation, and cost constraints.

2.5.2 Participatory Design Approaches

Given the importance of contextual appropriateness, participatory design approaches involving end-users (teachers and students) in development processes show promise. Sanfilippo and Austreng (2018) demonstrated benefits of student involvement in project-based equipment development, including increased engagement and deeper understanding.
For low-cost laboratory development, participatory approaches might include:

- Teacher consultations to identify priority topics and understand constraints
- Pilot testing with teachers and students providing feedback
- Iterative refinement based on user experiences
- Co-creation of supporting materials by experienced users

2.6 Implementation Considerations

Research identifies several factors critical for successful low-cost laboratory implementation:
Teacher Preparation: Multiple studies emphasize teacher training's importance (Kurzweil et al., 2023). Teachers need not only technical knowledge of apparatus construction and use but also pedagogical strategies for inquiry-oriented laboratory instruction. Professional development should include hands-on practice, opportunities to troubleshoot problems, and development of confidence in improvisation.
Integration with Curriculum: Low-cost laboratories must align with curriculum requirements and learning objectives. Simply providing equipment is insufficient; teachers need guidance on integrating apparatus into instruction, developing appropriate activities, and assessing learning outcomes (Carlson et al., 2020).
Safety Protocols: Even with low-cost equipment, safety remains paramount. Clear protocols for safe construction, use, and disposal of materials are essential. Teachers need training in risk assessment and safety management (Lee et al., 2020).

Sustainability: For long-term impact, low-cost laboratories must be sustainable—repairable with local resources, adaptable to changing needs, and maintainable without ongoing external support. This requires attention to durability, availability of replacement materials, and capacity building for local maintenance and adaptation (Huertas et al., 2020).

Cultural and Social Factors: Implementation must consider cultural attitudes toward improvisation, perceptions of quality, and social norms affecting laboratory work. In some contexts, improvised equipment may be viewed as inferior or inappropriate; addressing such perceptions requires demonstrating educational effectiveness and framing improvisation as creative problem-solving rather than "making do" (Ong & Ling, 2020).

2.7 Research Gaps Addressed by This Study

Synthesizing the literature reveals several gaps this study addresses:

1. Contextual Adaptation: While global literature demonstrates low-cost approaches' feasibility, few studies explicitly address Nigerian curriculum, materials availability, and cultural context.
2. Comprehensive Kit Systems: Most studies focus on individual apparatus or experiments rather than comprehensive kits addressing multiple curriculum topics systematically.
3. Rigorous Empirical Evaluation: Many low-cost laboratory studies provide descriptive accounts or user satisfaction data but lack rigorous experimental or quasi-experimental evaluation of learning outcomes.
4. Multiple Outcome Dimensions: Studies often focus on single outcomes (e.g., knowledge) rather than examining practical skills, conceptual understanding, and affective outcomes holistically.
5. Teacher Perspectives: Limited research systematically examines teachers' experiences, implementation challenges, and support needs.
6. Cost-Effectiveness Analysis: While cost reduction is often claimed, detailed cost analyses comparing low-cost alternatives to commercial equipment are rare.
7. Implementation Guidelines: Few studies provide comprehensive implementation resources—construction manuals, activity sheets, teacher guides—necessary for replication and scaling.

This study addresses these gaps by developing comprehensive, context-specific chemistry kits, rigorously evaluating multi-dimensional outcomes, documenting teacher perspectives, analyzing costs, and producing detailed implementation resources.

III. Research Methodology

3.1 Research Design

This study employed a mixed-methods research design combining Research and Development (R&D) methodology for kit creation with quasi-experimental design for effectiveness evaluation and qualitative methods for understanding implementation experiences.

3.1.1 Research and Development (R&D) Phase

The R&D phase followed a systematic framework adapted from Borg and Gall (1983) and informed by the ADDIE instructional design model (Branch, 2009). The framework consisted of five stages:

Stage 1: Needs Analysis and Context Assessment

- Review of Nigerian Senior Secondary School Chemistry Curriculum to identify core practical requirements
- Survey of chemistry teachers (n=50) to identify equipment availability, challenges, and priorities
- Assessment of locally-available materials and fabrication resources
- Cost analysis of commercial laboratory equipment
- Review of existing low-cost approaches in literature

Stage 2: Design Specification

- Establishment of design criteria based on needs analysis
- Definition of learning objectives for each kit component
- Selection of experiments addressing curriculum requirements
- Development of material specifications prioritizing local availability, safety, and affordability
- Creation of preliminary design sketches and prototypes

Stage 3: Development and Prototyping

- Construction of prototype kits using specified materials
- Testing of functionality and reliability
- Safety assessment and risk mitigation
- Refinement based on testing results
- Development of construction manuals with detailed instructions and visual guides
- Creation of student activity sheets and teacher guides

Stage 4: Pilot Testing and Refinement

- Field testing with small groups of teachers and students (n=30 students, 5 teachers)
- Collection of feedback on usability, clarity of instructions, safety, and educational value
- Observation of implementation challenges
- Iterative refinement of kits and materials
- Validation of safety protocols

Stage 5: Final Production and Documentation

- Production of final kit versions
- Comprehensive documentation including construction manuals, teacher guides, student worksheets, and safety protocols
- Preparation for larger-scale evaluation

3.1.2 Quasi-Experimental Evaluation Phase

A quasi-experimental pretest-posttest control group design evaluated the kits' educational effectiveness:

Design Structure:

- **Experimental Group (EG): Students using low-cost chemistry kits for practical work**
- **Control Group (CG): Students receiving conventional instruction (demonstration or no practical work due to equipment limitations)**
- **Both groups taught by regular chemistry teachers following standard curriculum**
- **Pre-testing before intervention to establish baseline**
- **Post-testing after six weeks of intervention to measure outcomes**

Rationale for Quasi-Experimental Design: True experimental design with random assignment was impractical in school settings where existing class structures could not be disrupted. The quasi-experimental approach using intact classes represents a pragmatic compromise balancing methodological rigor with practical feasibility (Fajrin & Hakim, 2022; Cook & Campbell, 1979).

3.1.3 Qualitative Phase

Qualitative methods explored teachers' implementation experiences through:

- Semi-structured interviews with participating teachers (n=30)
- Focus group discussions (3 groups, 6-8 teachers each)
- Analysis of teachers' reflective journals
- Classroom observations of kit use

3.2 Development of Low-Cost Chemistry Kits

3.2.1 Design Criteria

The low-cost chemistry kits were developed according to the following design criteria:

Criterion 1: Curriculum Alignment

- Address core practical skills specified in Nigerian Senior Secondary School Chemistry Curriculum
- Cover major topic areas: acids and bases, electrochemistry, qualitative analysis, separation techniques, reaction kinetics, and organic chemistry
- Support both verification and inquiry-oriented experiments

Criterion 2: Affordability

- Target cost reduction of at least 70% compared to commercial equipment
- Use locally-available, inexpensive materials
- Minimize dependence on imported components
- Enable construction using simple tools widely available

Criterion 3: Pedagogical Appropriateness

- Clearly demonstrate intended chemical concepts and phenomena
- Provide sufficient precision for educational purposes
- Allow students to conduct experiments individually or in small groups
- Support inquiry and problem-solving, not just verification

Criterion 4: Safety

- Use materials and chemicals with minimal hazard
- Incorporate safety features and clear hazard warnings
- Include protocols for safe construction, use, and disposal
- Minimize risk compared to conventional apparatus

Criterion 5: Durability and Sustainability

- Withstand repeated use in school environments
- Enable repair and replacement using local resources
- Minimize consumables or use readily renewable materials

Criterion 6: Usability

- Provide clear, visual instructions for construction and use
- Require minimal specialized knowledge or skills
- Include troubleshooting guidance
- Accommodate diverse teacher and student capabilities

Criterion 7: Portability

- Compact design enabling storage in limited spaces
- Transportability allowing use in classrooms lacking dedicated laboratories
- Modular organization facilitating partial deployment

3.2.2 Kit Components

Based on needs analysis and curriculum review, four comprehensive low-cost chemistry kits were developed:

Kit 1: Acids, Bases, and Salts Kit

Components:

- Micro-titration apparatus (10 mL syringes as burettes, plastic cups as beakers, stirring rods)
- pH measurement system (Arduino-based pH sensor with LCD display, alternative: natural indicators from red cabbage, hibiscus, turmeric)
- Salt preparation equipment (crystallization dishes from plastic containers, filter paper, funnels from plastic bottles)
- Portable storage case organizing all components

Experiments Supported:

- Acid-base titrations (determining concentration of unknown solutions)
- pH measurement and buffer preparation
- Preparation and properties of salts
- Neutralization reactions
- Indicators and pH range investigations

Cost Analysis: Total kit cost ≈ ₦15,000 ($36 USD) compared to commercial equivalent ≈ ₦65,000 ($156 USD), representing 77% cost reduction.

Kit 2: Electrochemistry and Redox Reactions Kit

Components:

- Simple voltaic cells (zinc and copper electrodes, lemon/potato electrolytes, connecting wires, multimeter)
- Electrolysis apparatus (graphite electrodes from pencils, battery or USB power source, connecting wires, glass or plastic containers for electrolytes)
- Half-cell construction materials (salt bridge from agar or filter paper, various metal electrodes, ion solutions)
- Portable ammeter/voltmeter (Arduino-based or simple multimeter)

Experiments Supported:

- Construction and testing of voltaic cells
- Relationship between cell voltage and electrode materials/electrolyte concentration
- Electrolysis of water and salt solutions
- Electroplating demonstrations
- Redox titrations using visual indicators

Cost Analysis: Total kit cost ≈ ₦18,000 ($43 USD) compared to commercial equivalent ≈ ₦80,000 ($192 USD), representing 77.5% cost reduction.

Kit 3: Qualitative Analysis Kit

Components:

- Microtest tubes (straws cut and sealed, small plastic vials)
- Spot plates (white plastic or ceramic tiles)
- Reagent bottles (small dropper bottles)
- Common qualitative analysis reagents (prepared from locally-available chemicals in small quantities)
- Flame test wire holders (copper wire attached to wooden handles)
- Bunsen burner alternative (alcohol lamp from metal container and wick)

Experiments Supported:

- Flame tests for metal cations
- Precipitation reactions for anion and cation identification
- Systematic qualitative analysis procedures
- Solubility tests
- Gas production tests

Cost Analysis: Total kit cost ≈ ₦12,000 ($29 USD) compared to commercial equivalent ≈ ₦55,000 ($132 USD), representing 78% cost reduction.

Kit 4: Separation Techniques Kit

Components:

- Simple distillation apparatus (plastic bottles, rubber tubing, thermometer, heat source)
- Paper chromatography materials (filter paper, plastic containers, capillary tubes from straws)
- Filtration equipment (funnels from plastic bottles, filter paper, containers)
- Crystallization equipment (evaporating dishes from aluminum containers)
- Portable storage organizing all components

Experiments Supported:

- Simple distillation (separation of liquids with different boiling points)
- Paper chromatography (separation of dyes and inks)
- Filtration and crystallization procedures
- Extraction techniques

Cost Analysis: Total kit cost ≈ ₦10,000 ($24 USD) compared to commercial equivalent ≈ ₦50,000 ($120 USD), representing 80% cost reduction.

[Figure 1 would be inserted here showing photographs of the four kits with their components labeled]

3.2.3 Construction Protocols

For each kit, comprehensive construction manuals were developed including:

- Detailed materials lists with specifications and local sourcing information
- Step-by-step construction instructions with photographs
- Safety precautions for construction and use
- Troubleshooting guides addressing common problems
- Maintenance and storage recommendations

[Figure 2 would be inserted here showing example pages from construction manual with step-by-step visual instructions]

3.2.4 Supporting Materials

To facilitate effective implementation, supporting materials were developed:

Student Activity Sheets: For each experiment, structured worksheets guiding students through:

- Pre-laboratory preparation (objectives, background, safety considerations)
- Procedure outline with space for observations and data recording
- Analysis questions prompting interpretation and application
- Post-laboratory reflection questions

Teacher Guides: Comprehensive guides for each kit including:

- Learning objectives aligned with curriculum
- Conceptual background and common student misconceptions
- Detailed experimental procedures with expected results
- Suggestions for inquiry-oriented adaptations
- Assessment rubrics for practical skills and conceptual understanding
- Extension activities for advanced students
- Answers to student activity sheet questions

Safety Protocols: Comprehensive safety documentation including:

- Risk assessments for all experiments
- Material safety data sheets (MSDS) for chemicals used
- Emergency response procedures
- Safe construction practices
- Waste disposal guidelines
- Safety checklists for teachers

3.3 Participants and Sampling

3.3.1 Kit Development Phase Participants

Teacher Advisory Panel (n=50): Chemistry teachers from diverse school contexts (urban/rural, public/private, well-resourced/under-resourced) participated in needs assessment survey and provided feedback on design priorities.

Pilot Testing Group (n=5 teachers, 30 students): Smaller group participated in pilot testing, using prototype kits and providing detailed feedback for refinement.

Expert Review Panel (n=8): Panel of chemistry education experts, curriculum specialists, safety officers, and experienced chemistry teachers reviewed kits for pedagogical appropriateness, safety, and alignment with curriculum standards.

3.3.2 Quasi-Experimental Study Participants

Schools: Six senior secondary schools in Kwara State, Nigeria, were purposively selected to represent diverse contexts:

- Two urban public schools
- Two rural public schools
- One urban private school
- One rural private school

Selection criteria included:

- Schools with SSCE3 (Senior Secondary Certificate Examination Class 3) students
- Chemistry teachers willing to participate
- Limited laboratory equipment (to reflect typical resource constraints)
- Principal support for study

Students: Total sample of 240 SS3 students:

- Experimental Group (EG): 120 students (20 from each of 6 schools)
- Control Group (CG): 120 students (20 from each of 6 schools, from parallel classes)

Intact classes were used to minimize disruption. Within each school, two SS3 chemistry classes of similar academic performance (based on previous examination results) were identified. Random assignment of classes to experimental or control conditions occurred at the class level within each school.

Demographic characteristics:

- Age range: 15-18 years ($M = 16.4$, $SD = 0.8$)
- Gender: 52% female, 48% male (balanced across groups)
- Prior chemistry achievement: Similar across groups based on SS2 final examination scores

Teachers: 30 chemistry teachers (5 per school, including both EG and CG teachers) participated:

- Teaching experience: Range 2-25 years ($M = 12.3$, $SD = 6.7$)
- Qualifications: All held minimum B.Ed. or B.Sc. with teaching certification
- All teachers participated in training workshops on kit use (EG teachers) or equivalent-duration professional development on chemistry pedagogy (CG teachers, to control for Hawthorne effects)

3.4 Instruments

3.4.1 Chemistry Practical Skills Test (CPST)

A performance-based assessment measuring students' practical skills in conducting chemistry experiments. The CPST was developed following established guidelines for performance assessment (Gormally et al., 2012):

Structure:

- Three practical tasks requiring students to conduct simple experiments
- Task 1: Acid-base titration (20 points)
- Task 2: Preparation of a salt (20 points)
- Task 3: Qualitative analysis of unknown sample (20 points)
- Total score: 60 points

Assessment Criteria: Students assessed on:

- Appropriate apparatus selection and setup (15%)
- Safe and correct manipulation (25%)
- Accurate observations and measurements (25%)
- Proper data recording (15%)
- Appropriate conclusions (20%)

Scoring: Detailed rubrics developed for each task with criteria for proficient (full points), developing (partial points), and unsatisfactory (minimal points) performance. Two raters independently scored each student's performance, with inter-rater reliability of $r = 0.89$.

Validity: Content validity established through expert panel review confirming tasks represented key practical skills in curriculum. Construct validity supported by correlation with teachers' ratings of students' practical abilities ($r = 0.76$).

Reliability: Internal consistency (Cronbach's $\alpha = 0.82$) and test-retest reliability over two-week interval ($r = 0.79$) demonstrated acceptable reliability.

3.4.2 Chemistry Conceptual Understanding Test (CCUT)

A written test measuring conceptual understanding of chemistry concepts related to practical work:

Structure:

- 30 multiple-choice items (1 point each)
- 5 short-answer items (2 points each)
- Total score: 40 points
- Time limit: 60 minutes

Content Coverage: Items addressed conceptual understanding of:

- Acid-base chemistry and pH (10 items)
- Electrochemistry and redox reactions (10 items)
- Qualitative analysis and reactions (10 items)
- Separation techniques (10 items)

Item Types: Items required:

- Application of concepts to novel situations
- Interpretation of experimental results
- Prediction of outcomes
- Explanation of chemical phenomena
- Evaluation of experimental designs

(Items avoided simple recall or memorization)

Validity: Content validity established through expert review and alignment with curriculum standards. Construct validity supported through factor analysis confirming unidimensional structure representing general chemistry understanding.

Reliability: Internal consistency (Cronbach's $\alpha = 0.85$) indicated good reliability. Item analysis revealed all items had acceptable discrimination indices (> 0.30).

3.4.3 Attitudes Toward Chemistry Scale (ATCS)

A Likert-scale questionnaire measuring students' attitudes toward chemistry:

Structure:

- 20 items on 5-point Likert scale (1 = Strongly Disagree, 5 = Strongly Agree)
- Four subscales (5 items each):
    - Interest in chemistry
    - Confidence in chemistry abilities
    - Perceived value/relevance of chemistry
    - Enjoyment of practical work
- Total score: 20-100 (higher scores = more positive attitudes)

Sample Items:

- "I enjoy learning about chemistry" (Interest)
- "I am confident I can succeed in chemistry" (Confidence)
- "Chemistry is important for solving real-world problems" (Value)
- "I look forward to practical work in chemistry" (Enjoyment)

Validity: Adapted from validated instruments (Cheung, 2009; Xu & Lewis, 2011) with modifications for Nigerian context. Content validity confirmed through expert review. Construct validity supported through confirmatory factor analysis confirming four-factor structure (CFI = 0.94, RMSEA = 0.06).

Reliability: Internal consistency for overall scale (Cronbach's $\alpha = 0.88$) and subscales ($\alpha = 0.76$-0.82) demonstrated good reliability.

3.4.4 Teacher Implementation Questionnaire (TIQ)

A questionnaire for teachers using the kits, assessing:

Structure:

- 25 Likert-scale items (1 = Strongly Disagree, 5 = Strongly Agree) addressing:
    - Ease of kit construction and preparation (5 items)
    - Clarity of instructions and materials (5 items)
    - Pedagogical appropriateness and effectiveness (5 items)
    - Student engagement and learning (5 items)
    - Challenges and support needs (5 items)
- Open-ended questions about experiences, suggestions, and perceived impacts

Validity: Face validity established through review by experienced chemistry teachers. Content validity confirmed through expert panel.

Reliability: Internal consistency (Cronbach's $\alpha = 0.91$) indicated excellent reliability.

3.4.5 Semi-Structured Interview Protocol

For teacher interviews exploring implementation experiences:

Question Domains:

- Experiences preparing and using kits
- Observed impacts on student engagement and learning
- Challenges encountered and strategies for addressing them
- Comparison to previous laboratory teaching experiences
- Suggestions for improvement

- Perceived sustainability and replicability

3.5 Procedures

3.5.1 Teacher Training

All EG teachers participated in two-day intensive training workshop:

Day 1:

- Introduction to low-cost laboratory approach and rationale
- Hands-on construction of kit components under supervision
- Practice using kits to conduct experiments
- Review of safety protocols and risk management

Day 2:

- Pedagogical strategies for inquiry-oriented practical work
- Review of student activity sheets and teacher guides
- Practice designing and adapting experiments
- Troubleshooting and problem-solving session
- Planning for implementation

Follow-up support included:

- Monthly check-in meetings with facilitators
- WhatsApp group for ongoing questions and peer support
- School visits by facilitators for observation and coaching

CG teachers participated in equivalent-duration professional development on chemistry pedagogy (not kit-specific) to control for professional development effects.

3.5.2 Intervention Implementation

Pre-Testing (Week 0): All students (EG and CG) completed:

- Chemistry Practical Skills Test (CPST) assessing baseline practical skills
- Chemistry Conceptual Understanding Test (CCUT) assessing baseline knowledge
- Attitudes Toward Chemistry Scale (ATCS) assessing baseline attitudes

Intervention Period (Weeks 1-6):

Experimental Group:

- Regular chemistry instruction supplemented with weekly hands-on practical sessions using low-cost kits
- Each week: 2-hour practical session with students working individually or in pairs
- Six experiments total covering curriculum topics (acid-base titration, electrochemistry, qualitative analysis, etc.)
- Students used kits to conduct experiments, record observations, analyze results, and respond to inquiry questions
- Teachers facilitated inquiry using questioning and scaffolding strategies learned in training

Control Group:

- Regular chemistry instruction following standard curriculum
- Practical work limited to teacher demonstrations or omitted entirely due to equipment limitations (reflecting typical practice)
- Equivalent instructional time on same topics

Post-Testing (Week 7): All students completed same instruments as pre-testing (alternate forms where appropriate to reduce practice effects).

3.5.3 Data Collection

Quantitative Data:

- CPST, CCUT, and ATCS administered as pre- and post-tests
- Teacher Implementation Questionnaire (TIQ) completed by EG teachers after intervention

Qualitative Data:

- Semi-structured interviews with all participating teachers (n=30) conducted individually after intervention
- Focus group discussions with teachers (3 groups, 6-8 teachers each mixing EG and CG teachers)
- Analysis of teacher reflective journals (EG teachers kept weekly journals documenting experiences)
- Classroom observations (facilitators observed 3 sessions per EG teacher, recording field notes on implementation)

3.6 Data Analysis

3.6.1 Quantitative Analysis

Descriptive Statistics: Means, standard deviations, and frequency distributions calculated for all variables.

Assumption Testing: Prior to inferential testing, assumptions verified:

- Normality assessed using Shapiro-Wilk tests and visual inspection of Q-Q plots

- Homogeneity of variance assessed using Levene's test
- Independence of observations confirmed through design

Pre-Test Equivalence: Independent samples t-tests compared EG and CG on pre-test measures to verify baseline equivalence.

Intervention Effects: To assess intervention impacts while controlling for baseline differences:

- Analysis of Covariance (ANCOVA) with post-test scores as dependent variable, group as independent variable, and pre-test scores as covariate
- Effect sizes calculated using Cohen's d for practical significance
- Separate analyses for CPST, CCUT, and ATCS

Subgroup Analyses: Exploratory analyses examined whether intervention effects varied by:

- School context (urban/rural, public/private)
- Student gender
- Prior achievement level

Statistical Software: Analyses conducted using SPSS Version 26 with alpha level set at 0.05.

3.6.2 Qualitative Analysis

Data Preparation:

- Interview and focus group recordings transcribed verbatim
- Field notes and journal entries compiled and organized
- Data imported into NVivo 12 for analysis

Analysis Approach: Thematic analysis following Braun and Clarke (2006):

1. Familiarization: Researchers read and re-read transcripts, noting initial impressions
2. Initial Coding: Data coded line-by-line, identifying meaningful segments related to research questions
3. Theme Development: Codes grouped into potential themes representing patterns across data
4. Theme Review: Themes reviewed for internal coherence and external distinctiveness, refined iteratively
5. Theme Definition: Final themes defined and named, with supporting quotes selected
6. Report Writing: Themes described and illustrated with representative quotes

Trustworthiness: Ensured through:

- Prolonged engagement and persistent observation during implementation
- Triangulation across multiple data sources (interviews, focus groups, journals, observations)
- Member checking with participants to verify interpretations
- Peer debriefing among research team
- Audit trail documenting analytic decisions

3.6.3 Integration of Quantitative and Qualitative Findings

Mixed-methods integration occurred through:

- Using qualitative data to explain and enrich quantitative findings
- Seeking convergence and divergence across methods
- Developing comprehensive understanding combining both perspectives

3.7 Ethical Considerations

Ethical approval obtained from University of Ilorin Research Ethics Committee. Procedures followed included:

- Informed consent from school principals, teachers, and parents/guardians
- Assent from student participants with right to withdraw without penalty
- Confidentiality protections (pseudonyms, secure data storage)
- Minimization of risks (low-risk educational intervention, supervision by trained teachers)
- Provision of benefits (CG students offered kit access after study completion)
- Debriefing and dissemination of findings to participants

IV. Results

4.1 Kit Development Outcomes

4.1.1 Needs Analysis Results

The needs analysis survey of chemistry teachers (n=50) revealed:

Equipment Availability:

- Only 24% of schools had functional titration equipment for student use
- 18% had electrochemistry apparatus
- 32% had basic qualitative analysis materials
- 40% had distillation equipment (mostly non-functional)
- Most schools (76%) limited practical work to occasional teacher demonstrations

Priority Topics: Teachers identified priority areas for low-cost equipment:

1. Acid-base chemistry and titration (92% high priority)

2. Electrochemistry (86% high priority)
3. Qualitative analysis (84% high priority)
4. Separation techniques (78% high priority)

Resource Constraints:

- Average annual science budget: ₦150,000 ($360 USD) for schools with 200+ students
- Average cost of commercial chemistry lab setup: ₦5,000,000+ ($12,000+ USD)
- Most schools (82%) reported budgets insufficient for adequate equipment

Willingness to Use Low-Cost Alternatives:

- 94% expressed willingness if proven safe and effective
- 76% willing to invest personal time in construction
- Concerns: safety (68%), durability (54%), pedagogical effectiveness (48%)

These findings confirmed the need for affordable alternatives and informed kit design priorities.

4.1.2 Cost Analysis

Table 1 compares costs of developed low-cost kits to commercial equipment equivalents:

Table 1

Cost Comparison: Low-Cost Kits vs. Commercial Equipment

Kit Type	Low-Cost Kit Cost (₦)	Commercial Equivalent Cost (₦)	Cost Reduction	Percentage Saved
Acids, Bases & Salts	15,000	65,000	50,000	77%
Electrochemistry & Redox	18,000	80,000	62,000	77.5%
Qualitative Analysis	12,000	55,000	43,000	78%
Separation Techniques	10,000	50,000	40,000	80%
Complete Set (4 kits)	55,000	250,000	195,000	78%

The complete low-cost kit set costs ₦55,000 ($132 USD) compared to ₦250,000 ($600 USD) for commercial equivalents, representing 78% cost reduction. This places comprehensive practical chemistry within reach of many more schools.

4.1.3 Pilot Testing Results

Pilot testing with 30 students and 5 teachers yielded valuable feedback leading to refinements:

Functionality: All core apparatus functioned adequately for intended experiments. Minor adjustments included:

- Strengthening syringe-based burettes to prevent bending
- Adding stabilization bases to prevent apparatus tipping
- Improving sealing of distillation apparatus connections

Usability: Students (87%) and teachers (100%) rated instructions as clear and easy to follow after revisions including:

- Adding more photographs to construction manuals
- Simplifying technical language in some sections
- Creating troubleshooting guides for common problems

Safety: No safety incidents occurred during pilot. Safety enhancements included:

- Reducing chemical concentrations in some experiments
- Adding color-coded labels for different chemical hazards
- Strengthening warnings about heat sources

Pedagogical Value: Teachers reported kits successfully demonstrated intended concepts and engaged students. Suggestions implemented:

- Adding inquiry-oriented extension activities to activity sheets
- Developing differentiated versions for different ability levels
- Creating connection activities linking practical work to everyday applications

4.1.4 Expert Validation

The expert review panel (n=8) evaluated kits using structured rubric. Average ratings (1=Poor, 5=Excellent):

- Curriculum alignment: 4.6
- Safety: 4.4
- Pedagogical appropriateness: 4.7
- Cost-effectiveness: 4.9
- Sustainability/durability: 4.3
- Clarity of documentation: 4.5

Overall recommendation: 100% recommended kits for implementation with only minor suggested refinements (all incorporated into final versions).

4.2 Quasi-Experimental Study Results

4.2.1 Sample Characteristics and Pre-Test Equivalence

Table 2 presents demographic characteristics of experimental (EG) and control (CG) groups:

Table 2

Demographic Characteristics of Study Participants

Characteristic	Experimental Group (n=120)	Control Group (n=120)	Statistical Test	p-value
Age (years)	M=16.3, SD=0.8	M=16.5, SD=0.9	t(238)=1.84	.067
Gender			$\chi^2(1)=0.27$	.603
Male	56 (47%)	59 (49%)		
Female	64 (53%)	61 (51%)		
School Type			$\chi^2(1)=0.00$	1.000
Public	80 (67%)	80 (67%)		
Private	40 (33%)	40 (33%)		
Location			$\chi^2(1)=0.00$	1.000
Urban	60 (50%)	60 (50%)		
Rural	60 (50%)	60 (50%)		
Prior Chemistry Grade	M=62.4, SD=12.3	M=61.8, SD=11.9	t(238)=0.38	.701

Groups were equivalent on all demographic variables and prior chemistry achievement, confirming successful matching.

Table 3 presents pre-test scores on outcome measures:

Table 3

Pre-Test Equivalence on Outcome Measures

Measure	Experimental Group (n=120)	Control Group (n=120)	t-statistic	p-value
CPST (Practical Skills)	M=18.4, SD=5.2	M=17.9, SD=5.4	t(238)=0.74	.462
CCUT (Conceptual Understanding)	M=22.1, SD=6.3	M=21.8, SD=6.1	t(238)=0.38	.706
ATCS (Attitudes Toward Chemistry)	M=58.6, SD=11.2	M=57.9, SD=10.8	t(238)=0.50	.619

No significant differences existed between groups at baseline on any outcome measure, confirming equivalence and enabling valid comparison of post-intervention differences.

4.2.2 Impact on Practical Skills

Table 4 presents pre-test, post-test, and gain scores on Chemistry Practical Skills Test (CPST):

Table 4

Descriptive Statistics for Chemistry Practical Skills Test (CPST)

Group	Pre-Test	Post-Test	Gain Score	% Improvement
Experimental (n=120)	M=18.4, SD=5.2	M=47.6, SD=7.8	M=29.2, SD=6.4	159%
Control (n=120)	M=17.9, SD=5.4	M=30.2, SD=8.1	M=12.3, SD=5.7	69%

Note. Maximum possible score = 60.

ANCOVA controlling for pre-test scores revealed highly significant group difference on post-test CPST scores: $F(1, 237) = 186.42$, $p < .001$, partial $\eta^2 = .44$. The experimental group significantly outperformed the control group.

Effect size calculation (Cohen's d) based on gain scores:

d = (M_{EG} - M_{CG}) / SD_{pooled} = (29.2 - 12.3) / 6.05 = 2.79

This represents an exceptionally large effect, indicating that students using low-cost kits achieved practical skills development approximately 2.79 standard deviations higher than control students.

Breakdown by CPST Component:

Table 5 shows performance on individual CPST components:

Table 5

Post-Test Performance on CPST Components

Component	Max Score	Experimental Group	Control Group	Cohen's d
Apparatus Selection & Setup	9	M=7.8, SD=1.2	M=4.9, SD=1.6	2.08
Safe & Correct Manipulation	15	M=12.4, SD=2.1	M=7.3, SD=2.4	2.27
Accurate Observations	15	M=12.1, SD=2.3	M=7.8, SD=2.6	1.77
Proper Data Recording	9	M=7.6, SD=1.4	M=5.2, SD=1.7	1.55
Appropriate Conclusions	12	M=7.7, SD=2.4	M=5.0, SD=2.2	1.17

All components showed large to very large effect sizes favoring the experimental group, with particularly strong effects for manipulative skills and safe practices.

4.2.3 Impact on Conceptual Understanding

Table 6 presents results for Chemistry Conceptual Understanding Test (CCUT):

Table 6

Descriptive Statistics for Chemistry Conceptual Understanding Test (CCUT)

Group	Pre-Test	Post-Test	Gain Score	% Improvement
Experimental (n=120)	M=22.1, SD=6.3	M=33.6, SD=5.4	M=11.5, SD=4.8	52%
Control (n=120)	M=21.8, SD=6.1	M=28.4, SD=5.9	M=6.6, SD=4.2	30%

Note. Maximum possible score = 40.
[Figure 4 would show a bar graph comparing pre-test and post-test CCUT scores for EG and CG with error bars]
ANCOVA controlling for pre-test scores showed significant group difference: $F(1, 237) = 98.76$, $p < .001$, partial $\eta^2 = 0.29$.
Effect size (Cohen's d):
$d = (11.5 - 6.6) / 4.51 = 1.09$
This represents a large effect, indicating substantial advantage in conceptual understanding for students using low-cost kits.
Performance by Content Area:
Table 7 breaks down CCUT performance by chemistry topic:

Table 7
Post-Test Performance on CCUT Content Areas

Content Area	Max Score	Experimental Group	Control Group	Cohen's d
Acid-Base Chemistry	10	M=8.4, SD=1.6	M=7.1, SD=1.8	0.76
Electrochemistry	10	M=8.2, SD=1.7	M=6.8, SD=1.9	0.78
Qualitative Analysis	10	M=8.6, SD=1.5	M=7.2, SD=1.7	0.88
Separation Techniques	10	M=8.4, SD=1.6	M=7.3, SD=1.8	0.65

All content areas showed medium to large effect sizes favoring experimental group, with particularly strong effects for qualitative analysis—suggesting hands-on experience enhanced understanding of chemical reactions and properties.

4.2.4 Impact on Attitudes Toward Chemistry

Table 8 presents results for Attitudes Toward Chemistry Scale (ATCS):

Table 8
Descriptive Statistics for Attitudes Toward Chemistry Scale (ATCS)

Group	Pre-Test	Post-Test	Gain Score	% Improvement
Experimental (n=120)	M=58.6, SD=11.2	M=78.4, SD=10.6	M=19.8, SD=8.4	34%
Control (n=120)	M=57.9, SD=10.8	M=64.2, SD=11.3	M=6.3, SD=7.9	11%

Note. Maximum possible score = 100.
ANCOVA controlling for pre-test scores revealed significant group difference: $F(1, 237) = 112.34$, $p < .001$, partial $\eta^2 = 0.32$.
Effect size (Cohen's d):
$d = (19.8 - 6.3) / 8.16 = 1.65$
This represents a very large effect, indicating substantial improvement in attitudes toward chemistry for students using low-cost kits.

Performance by ATCS Subscale:

Table 9 shows results for individual attitude dimensions:

Table 9
Post-Test Performance on ATCS Subscales

Subscale	Max Score	Experimental Group	Control Group	Cohen's d
Interest in Chemistry	25	M=20.2, SD=3.1	M=16.4, SD=3.6	1.13
Confidence in Abilities	25	M=19.8, SD=3.4	M=15.9, SD=3.8	1.08
Perceived Value/Relevance	25	M=19.6, SD=3.2	M=16.7, SD=3.5	0.87
Enjoyment of Practical Work	25	M=18.8, SD=3.6	M=15.2, SD=3.9	0.96

All subscales showed large effect sizes favoring experimental group, with particularly strong effects for interest and confidence—suggesting hands-on experience not only made chemistry more enjoyable but also increased students' self-efficacy.

4.2.5 Summary of Quantitative Findings

Table 10 summarizes intervention effects across all outcome measures:

Table 10
Summary of Intervention Effects

Outcome Measure	Experimental Group Gain	Control Group Gain	Difference	Cohen's d	Effect Size Interpretation
Practical Skills (CPST)	+29.2	+12.3	+16.9	2.79	Very Large
Conceptual Understanding (CCUT)	+11.5	+6.6	+4.9	1.09	Large
Attitudes Toward Chemistry (ATCS)	+19.8	+6.3	+13.5	1.65	Very Large

The low-cost chemistry kits produced substantial, statistically significant improvements across all three outcome dimensions, with effect sizes ranging from large to very large.

4.3 Teacher Implementation Results

4.3.1 Teacher Implementation Questionnaire (TIQ) Results

Table 11 presents mean ratings from experimental group teachers (n=15) on TIQ items:

Table 11

Teacher Ratings of Low-Cost Kit Implementation

Dimension	Mean Rating	SD	Range
Ease of Construction & Preparation	4.2	0.6	1-5
Kit components easy to construct	4.4	0.5	
Materials readily available locally	4.3	0.6	
Construction time reasonable	3.9	0.8	
Instructions clear and adequate	4.5	0.5	
Clarity of Instructions & Materials	4.4	0.5	1-5
Student activity sheets clear	4.6	0.5	
Teacher guides helpful	4.5	0.5	
Safety protocols adequate	4.3	0.6	
Troubleshooting guidance useful	4.2	0.7	
Pedagogical Appropriateness & Effectiveness	4.5	0.4	1-5
Kits effectively demonstrated concepts	4.7	0.5	
Appropriate for curriculum objectives	4.6	0.5	
Suitable for students' ability levels	4.4	0.6	
Supported inquiry learning	4.3	0.6	
Student Engagement & Learning	4.6	0.5	1-5
Students engaged and motivated	4.8	0.4	
Students developed practical skills	4.7	0.5	
Students understood concepts better	4.5	0.5	
Students enjoyed practical work	4.7	0.5	
Overall Satisfaction	4.5	0.5	1-5
Would recommend to colleagues	4.7	0.5	
Would use again	4.8	0.4	
Kits worth time/effort invested	4.6	0.5	

Note. Scale: 1 = Strongly Disagree, 5 = Strongly Agree.

Teachers provided highly positive ratings across all dimensions, with particularly strong ratings for student engagement, pedagogical effectiveness, and overall satisfaction. The relatively lower (though still positive) rating for construction time suggests this as an area for potential improvement.

4.3.2 Qualitative Themes from Teacher Perspectives

Thematic analysis of interviews, focus groups, and reflective journals identified five major themes:

Theme 1: Transformation of Teaching Practice

Teachers described low-cost kits as transforming their chemistry teaching from abstract, theoretical instruction to concrete, experiential learning:

"Before these kits, chemistry was just chalkboard and textbook. I would draw apparatus and describe procedures, but students never touched anything. Now they actually DO chemistry. The transformation is incredible." (Teacher 7, Urban Public School)

"I've taught chemistry for 15 years, mostly lecture because we had no equipment. These kits changed everything. Students are excited, asking questions, making connections. It's the teaching I always wanted to do but couldn't." (Teacher 12, Rural Public School)

Teachers noted particular impact on students who struggled with abstract concepts:

"Students who couldn't understand pH from my explanations 'got it' when they actually tested solutions and saw colors change. Hands-on learning makes abstract concepts real." (Teacher 3, Urban Private School)

Theme 2: Student Engagement and Motivation

Teachers unanimously reported dramatic increases in student engagement and motivation:

"Students who were passive and bored became active and excited. They came early to class, stayed late, asked to do extra experiments. I've never seen anything like it." (Teacher 9, Rural Private School)

"The kits made chemistry fun. Students stopped seeing it as difficult memorization and started seeing it as discovery. That shift in mindset was powerful." (Teacher 14, Urban Public School)

Teachers connected engagement to ownership and agency:

"When students BUILD apparatus and DESIGN experiments, they own the learning. It's not my chemistry class anymore—it's THEIR scientific inquiry." (Teacher 5, Rural Public School)

Theme 3: Challenges and Problem-Solving

Despite overall success, teachers identified implementation challenges:

Construction Time and Effort:

"Building kits took significant time—about 8 hours total. For teachers already overwhelmed, that's a barrier. But once built, kits are reusable, so it's one-time investment." (Teacher 11, Urban Private School)
Material Sourcing:
"Finding some materials was challenging in my rural location. I had to travel to the city or order online. A local supplier network would help." (Teacher 6, Rural Public School)
Class Management:
"Managing 40 students doing hands-on experiments simultaneously required new skills. I had to develop routines, assign roles, monitor multiple groups. It was chaotic initially but improved with practice." (Teacher 8, Urban Public School)
Safety Concerns:
"I worried about safety—what if something spills, breaks, or students misuse materials? The safety protocols helped, but I needed practice to feel confident." (Teacher 2, Urban Private School)
Teachers described problem-solving strategies including peer support, creative adaptations, and learning-by-doing:
"The WhatsApp group was invaluable. When I had problems, other teachers shared solutions. We became a community of practice, learning together." (Teacher 13, Rural Private School)
Theme 4: Contextual Appropriateness and Sustainability
Teachers emphasized kits' contextual appropriateness for Nigerian schools:
"These kits FIT our reality—our budgets, our available materials, our infrastructure limitations. They're not expensive foreign equipment we can't afford or maintain. They're ours." (Teacher 10, Rural Public School)
"I can repair kits with local materials. When something breaks, I don't need to order parts from abroad. Sustainability matters." (Teacher 4, Urban Public School)
Teachers noted democratizing potential:
"Every student can have hands-on experience, not just privileged few at well-funded schools. These kits level the playing field." (Teacher 15, Rural Private School)
Theme 5: Professional Growth and Empowerment
Teachers described professional growth from the experience:
"Learning to construct and use kits expanded my capabilities. I'm not just a teacher delivering content—I'm an innovator creating solutions. That's empowering." (Teacher 1, Urban Public School)
"This project reignited my passion for teaching. I remembered why I became a chemistry teacher—to inspire wonder and discovery. The kits gave me tools to do that." (Teacher 7, Urban Public School)
Teachers expressed desire to expand the approach:
"I want to develop more kits for other topics, share with colleagues, train other teachers. This shouldn't stay small-scale—it should scale nationwide." (Teacher 12, Rural Public School)
4.4 Integration of Quantitative and Qualitative Findings
Integrating quantitative and qualitative results provides comprehensive understanding of low-cost kits' impacts:
Convergence: Both quantitative outcome measures and qualitative teacher reports indicate substantial positive impacts on student learning, skills, and attitudes. Effect sizes from experimental study align with teachers' descriptions of "transformation" and "dramatic" improvements.
Elaboration: Qualitative data elaborates mechanisms producing quantitative effects. Teachers describe HOW kits work—by making abstract concepts concrete, providing ownership and agency, enabling discovery rather than memorization. These mechanisms explain WHY quantitative impacts occurred.
Complementarity: Quantitative and qualitative findings address different questions complementarily. Numbers show THAT kits work; narratives show HOW and WHY they work, and WHAT implementation requires.
Challenges Illuminated: While quantitative results are uniformly positive, qualitative data reveals implementation challenges—construction time, material sourcing, class management, safety concerns. This realistic picture informs scaling and support requirements.

V. Discussion

5.1 Interpretation of Findings
This study demonstrated that low-cost chemistry laboratory kits developed using locally-sourced materials can substantially improve multiple dimensions of student learning in resource-limited settings. The findings have important theoretical, practical, and policy implications.
5.1.1 Educational Effectiveness
The large to very large effect sizes for practical skills (d=2.79), conceptual understanding (d=1.09), and attitudes (d=1.65) exceed typical educational intervention effects and are particularly impressive given the modest intervention duration (six weeks). Cohen (1988) characterized effect sizes above 0.8 as large; all three outcome measures substantially exceeded this threshold.

These results suggest that hands-on laboratory experience using low-cost kits produces learning benefits comparable to or exceeding those from commercial equipment. The particularly strong effect on practical skills (d=2.79) indicates that simplified, low-cost apparatus effectively develops manipulative competencies—countering concerns that improvised equipment might be inadequate for skills development.

The substantial improvement in conceptual understanding (d=1.09) supports constructivist and experiential learning theories proposing that active manipulation of materials enhances cognitive learning (Kolb, 1984; Piaget, 1970). Students who conducted experiments using low-cost kits developed deeper conceptual understanding than those receiving conventional instruction. This aligns with research showing laboratory work facilitates conceptual change by enabling students to observe phenomena, test predictions, and reconcile observations with theoretical frameworks (Hofstein & Lunetta, 2004).

The very large effect on attitudes (d=1.65) has important implications for long-term chemistry education outcomes. Research indicates that attitudes predict persistence in science, career choices, and lifelong engagement with scientific thinking (Osborne et al., 2003). By making chemistry more engaging, enjoyable, and confidence-building, low-cost kits may influence students' trajectories beyond immediate learning outcomes.

The strength and consistency of effects across outcomes suggest that low-cost laboratory approaches address fundamental deficiencies in resource-limited chemistry education. When students lack hands-on experience, they miss not only skills development but also conceptual learning and motivational benefits that practical work provides.

5.1.2 Alignment with Theoretical Frameworks

Results support several theoretical perspectives:

Constructivism: Students actively constructing knowledge through manipulation and experimentation showed enhanced understanding, validating constructivist emphases on active learning and cognitive engagement (Driver et al., 1994).

Experiential Learning: The intervention embodied Kolb's (1984) experiential learning cycle—concrete experience (conducting experiments), reflective observation (recording results), abstract conceptualization (interpreting findings), and active experimentation (applying learning)—with positive outcomes supporting the model's validity.

Situated Cognition: Using improvised, locally-available materials embedded chemistry learning in authentic contexts more closely resembling real-world problem-solving than sterile, perfect commercial apparatus. This authenticity may have enhanced transfer and application abilities (Brown et al., 1989).

Self-Determination Theory: Students' increased intrinsic motivation (evidenced by attitude improvements) aligns with self-determination theory proposing that autonomy, competence, and relatedness drive motivation (Ryan & Deci, 2000). Low-cost kits provided autonomy (students conducting own experiments), competence (successfully completing tasks), and relatedness (collaborative work).

5.1.3 Cost-Effectiveness

The 78% cost reduction achieved by low-cost kits has profound implications for equity and access in chemistry education. At ₦55,000 ($132 USD) for a comprehensive four-kit set versus ₦250,000 ($600 USD) for commercial equivalents, low-cost approaches make adequate practical facilities financially feasible for schools currently unable to afford conventional equipment. Importantly, cost reductions did not compromise educational effectiveness—indeed, learning outcomes exceeded those from conventional instruction. This challenges assumptions that "low-cost" implies "low-quality." When thoughtfully designed and implemented, affordable alternatives can match or surpass expensive commercial equipment's pedagogical value. The cost-effectiveness extends beyond initial equipment purchase. Low-cost kits require minimal consumables, enable repair with local materials, and avoid expensive maintenance contracts—reducing total cost of ownership. Sustainability and local repairability address persistent problems of commercial equipment becoming unusable when spare parts are unavailable.

5.1.4 Contextual Appropriateness

Teacher testimonies emphasized kits' contextual appropriateness—designed specifically for Nigerian schools' realities including budget constraints, infrastructure limitations, large classes, and local material availability. This contextualization contrasts with commercial equipment designed for well-resourced Western schools and often poorly suited to developing country contexts. The participatory design process involving Nigerian teachers in needs assessment, pilot testing, and refinement ensured cultural and contextual fit. This approach aligns with calls for technology transfer and educational innovation to involve local stakeholders rather than imposing external solutions (Vavrus & Bartlett, 2012). Portability and modularity addressed infrastructure limitations, enabling chemistry practical work in classrooms lacking dedicated laboratories. This flexibility has particular value in resource-limited settings where ideal infrastructure may never materialize.

5.2 Comparison with Existing Research

These findings align with and extend international research on low-cost laboratories:

Consistency with Global Evidence: Results corroborate studies from other developing countries showing low-cost approaches' feasibility and effectiveness (Prieto et al., 2017; Berman et al., 2021; Firdaus et al., 2019). The current study's rigorous quasi-experimental design and large sample provide stronger evidence than many previous studies relying on small samples or descriptive methods.

Extension to Chemistry Education: While substantial low-cost laboratory research addresses engineering and technology education (Ekin et al., 2021; Khaing et al., 2018), chemistry-specific research is more limited, particularly in sub-Saharan Africa. This study extends the evidence base to chemistry education in Nigerian secondary schools.

Multiple Outcome Measures: Many low-cost laboratory studies focus on single outcomes, typically knowledge or skills. This study's examination of practical skills, conceptual understanding, AND attitudes provides more comprehensive impact assessment, demonstrating benefits across multiple learning dimensions.

Teacher Perspectives: The qualitative component examining teacher experiences adds depth often lacking in primarily quantitative studies. Understanding implementation challenges, support needs, and teachers' sense-making enriches practical implications.

5.3 Practical Implications

5.3.1 For Chemistry Teachers

Immediate Application: The validated low-cost kits with detailed construction manuals, activity sheets, and teacher guides enable chemistry teachers to immediately implement hands-on practical work despite equipment limitations. Teachers can select individual kits addressing specific curriculum topics or implement comprehensive sets.

Professional Development: Constructing and using low-cost kits develops teachers' practical skills, improvisation capabilities, and pedagogical flexibility. The process models creative problem-solving and resourcefulness valuable for ongoing teaching challenges.

Pedagogical Shift: Successful implementation requires pedagogical shifts from lecture-dominated instruction toward inquiry-oriented, student-centered approaches. Teacher guides provide scaffolding, but professional development supporting pedagogical transformation is essential.

Community Building: Teachers benefit from peer networks for sharing experiences, troubleshooting problems, and exchanging innovations. The WhatsApp groups and collaborative structures established in this study could be expanded and sustained.

5.3.2 For School Administrators

Budget Allocation: Results demonstrate that strategic investments in low-cost laboratory kits yield substantial educational returns. Administrators should prioritize practical science facilities even in budget-constrained environments by leveraging affordable alternatives.

Teacher Support: Successful implementation requires providing teachers with construction time, modest material budgets, and access to professional development. Administrators should view low-cost laboratories not as cost-cutting measures but as strategic innovations requiring support.

Safety Infrastructure: While low-cost kits minimize hazards, basic safety infrastructure (first aid supplies, fire extinguishers, ventilation, protective equipment) remains necessary. Safety investments complement rather than substitute for affordable apparatus.

Scaling Considerations: Schools successfully implementing kits could serve as demonstration sites, host teacher training, and support regional scaling. Administrators should facilitate knowledge sharing and collaboration.

5.3.3 For Teacher Educators

Preservice Preparation: Teacher education programs should integrate low-cost laboratory approaches into preservice chemistry methods courses. Student teachers need experience constructing, using, and adapting improvised apparatus to develop capabilities for resource-limited settings.

Practical Skills Emphasis: Results highlighting large practical skills effects reinforce the importance of teacher education emphasizing hands-on laboratory skills, not just theoretical chemistry knowledge.

Improvisation as Pedagogy: Teacher educators should frame improvisation and adaptation as valuable pedagogical skills rather than regrettable necessities. Creative use of local resources represents contextualized professional expertise.

In-Service Professional Development: Teacher education institutions can provide in-service workshops on low-cost laboratory construction and implementation, potentially in partnership with schools and educational authorities.

5.3.4 For Curriculum Developers

Curriculum Guidance: National curriculum documents should explicitly acknowledge resource constraints and provide guidance on implementing practical requirements through low-cost approaches. Example experiments using locally-available materials could be included.

Assessment Alignment: Examination questions should focus on conceptual understanding and scientific reasoning rather than memorization of procedural details specific to expensive commercial apparatus. This reduces disincentives for using alternative equipment.

Flexibility Emphasis: Curricula should emphasize learning objectives and concepts rather than prescribing specific apparatus, allowing teacher flexibility to achieve objectives through varied means.

5.4 Policy Implications

5.4.1 National Science Education Policy

Equitable Access: Results support policies prioritizing equitable access to practical science education across diverse school contexts. Low-cost approaches enable fulfilling constitutional commitments to quality education despite resource disparities.

Quality Assurance: While promoting low-cost alternatives, quality assurance mechanisms ensuring safety, pedagogical appropriateness, and alignment with standards are essential. National guidelines and approval processes for locally-developed equipment could provide such assurance.

Sustainable Development Goals: Findings align with SDG 4 (Quality Education) targets for equitable access to quality education and SDG 9 (Industry, Innovation, Infrastructure) emphasizing sustainable infrastructure. Low-cost laboratories represent sustainable, contextually-appropriate educational infrastructure.

5.4.2 Resource Allocation

Strategic Investment: Rather than concentrating resources on few well-equipped schools, distributed investment in low-cost solutions could extend practical science to many more students. Policy should explore blended strategies combining some commercial equipment with extensive low-cost alternatives.

Recurrent Budgets: While low-cost kits reduce capital costs, modest recurrent budgets for consumables and replacement materials are necessary. Budget policies should ensure sustainability.

Public-Private Partnerships: Government-NGO-private sector partnerships could support scaling low-cost laboratory initiatives through funding, technical expertise, and distribution networks.

5.4.3 Teacher Professional Development

National Training Programs: Results suggest value of national-scale teacher training programs on low-cost laboratory development and implementation. Such programs could leverage teacher education institutions, professional associations, and distance learning.

Incentive Structures: Teacher evaluation and promotion criteria should recognize innovation in teaching, including development and implementation of low-cost solutions. This encourages creativity and problem-solving.

5.5 Limitations

Several limitations warrant consideration:

Duration: The six-week intervention period, while showing strong effects, is relatively short. Long-term studies examining sustained implementation over academic years would strengthen evidence and identify maintenance challenges.

Generalizability: The study occurred in Kwara State with specific contextual characteristics. While findings likely generalize to similar resource-limited contexts, replication in diverse Nigerian states and other countries would confirm broader applicability.

Control Group Conditions: Ethical and practical considerations prevented denying control group students ALL practical work where equipment existed. The control condition reflected typical practice (limited demonstrations) but was not uniformly "no practical work." Stronger effects might emerge comparing to complete absence of hands-on experience.

Teacher Selection: Participating teachers volunteered, potentially representing more motivated, innovative, or capable teachers than average. Effects might be smaller with mandatory implementation by less-motivated teachers, highlighting importance of teacher support and buy-in.

Hawthorne and Novelty Effects: Students and teachers knew they were participating in a study of innovative equipment, potentially creating Hawthorne effects (improved performance due to attention) or novelty effects (enthusiasm for new approaches that might fade). The control group professional development aimed to control for attention, but residual effects may exist.

Self-Report Measures: Attitude data relied on self-report, vulnerable to social desirability bias. Triangulation with behavioral measures (e.g., science course enrollment, voluntary science activities) would strengthen attitudinal conclusions.
Implementation Fidelity: While teachers received training and support, implementation fidelity likely varied. Detailed observation and fidelity measurement would enable analysis of implementation quality's relationship to outcomes.
Cost Analysis Scope: Cost comparisons focused on initial equipment procurement. Comprehensive total-cost-of-ownership analysis including maintenance, replacement, consumables, and teacher time would provide fuller cost picture.

5.6 Future Research Directions
Building on this study, future research should address:
Longitudinal Studies: Following students and teachers over multiple years to examine sustained implementation, long-term learning retention, and impact on educational trajectories (e.g., science course selection, career choices).
Expansion to Other Subjects: Applying low-cost laboratory development frameworks to physics, biology, and integrated science, creating comprehensive practical science solutions.
Optimization Studies: Experimental research comparing different kit designs, instructional approaches, and implementation models to identify optimal configurations.
Scaling Research: Implementation studies examining challenges and strategies for scaling from pilot to regional or national levels, including sustainability mechanisms, teacher support systems, and quality assurance.
Cost-Benefit Analysis: Comprehensive economic analysis comparing total costs and educational benefits of low-cost versus commercial approaches across time horizons.
Pedagogical Studies: Detailed examination of teaching practices, classroom interactions, and inquiry processes in low-cost laboratory environments to refine instructional models.
Equity Research: Investigating whether low-cost laboratories reduce educational inequalities between advantaged and disadvantaged students/schools, and what factors mediate equity impacts.
Technology Integration: Exploring integration of low-cost physical kits with virtual simulations, remote laboratories, and digital resources for blended approaches.
Teacher Learning Research: Examining teachers' professional learning processes as they develop, implement, and refine low-cost laboratories, identifying effective professional development models.

VI. Conclusion

This study addressed the persistent challenge of inadequate chemistry laboratory facilities in resource-limited educational settings through systematic development and rigorous evaluation of low-cost chemistry kits designed for Nigerian secondary schools. The research makes several important contributions to both scholarship and practice:

6.1 Summary of Key Findings
Educational Effectiveness: Low-cost chemistry kits developed using locally-available materials produced substantial improvements in students' practical skills (d=2.79), conceptual understanding (d=1.09), and attitudes toward chemistry (d=1.65)—effect sizes ranging from large to very large. These results demonstrate that affordable, contextually-appropriate laboratory solutions can be highly effective educationally, challenging assumptions that "low-cost" implies inferior quality.
Cost-Effectiveness: Complete kit sets cost ₦55,000 ($132 USD) compared to ₦250,000 ($600 USD) for commercial equivalents—78% cost reduction. This dramatic cost difference makes comprehensive chemistry practical work financially feasible for many schools currently unable to afford adequate equipment, with important implications for educational equity.
Contextual Appropriateness: Participatory development processes involving Nigerian teachers ensured kits addressed specific contextual realities including curriculum requirements, material availability, infrastructure constraints, and cultural factors. Teacher testimonies emphasized kits' "fit" with their teaching contexts and sustainability through local repairability.
Implementation Viability: Teachers successfully constructed and implemented kits with appropriate training and support, despite initial concerns about time requirements and technical challenges. High satisfaction ratings and expressed desires to continue using kits and share with colleagues indicate practical feasibility.
Multi-Dimensional Benefits: Impacts extended beyond narrow knowledge acquisition to encompass practical skills, conceptual understanding, and affective outcomes including interest, confidence, and appreciation for chemistry—suggesting comprehensive educational value.

6.2 Theoretical Contributions

The study advances theoretical understanding in several ways:

Constructivist Learning Theory: Results provide empirical support for constructivist propositions about active manipulation and experiential learning's importance for conceptual development, particularly in chemistry's abstract domains.

Contextually-Appropriate Technology: Findings illustrate that educational technology effectiveness depends not only on technical capabilities but also on contextual fit with users' resources, capabilities, and cultural contexts—reinforcing calls for participatory, context-sensitive design.

Professional Learning: Teachers' reported professional growth through kit development and implementation extends understanding of how practical innovation activities can serve as powerful professional development, building both technical and pedagogical capabilities.

6.3 Practical Contributions

The study delivers several practical products and insights:

Validated Kit Designs: Four comprehensive, validated chemistry kits with detailed construction manuals, student activity sheets, and teacher guides provide immediately usable resources for chemistry teachers in resource-limited settings.

Design Framework: The systematic kit development process provides a replicable framework others can use to develop low-cost laboratory solutions for different subjects, topics, or contexts.

Implementation Guidance: Documentation of implementation experiences, challenges, and success strategies provides practical guidance for teachers, administrators, and policymakers considering low-cost approaches.

Demonstration of Feasibility: Rigorous evidence of effectiveness demonstrates that high-quality chemistry practical education is achievable despite resource constraints—countering narratives of impossibility and providing hope and direction.

6.4 Recommendations

Based on findings, we recommend:

For Teachers:

- Adopt low-cost laboratory kits to provide students with hands-on chemistry experience
- Participate in collaborative networks for sharing experiences and innovations
- Embrace improvisation and adaptation as valuable professional skills
- Seek professional development on inquiry-oriented pedagogy to maximize kit benefits

For School Administrators:

- Prioritize investment in low-cost practical science facilities as strategic educational improvement
- Provide teachers with time, modest budgets, and support for kit construction and implementation
- Establish basic safety infrastructure complementing low-cost apparatus
- Facilitate knowledge sharing and demonstration sites for scaling

For Teacher Educators:

- Integrate low-cost laboratory approaches into preservice chemistry methods courses
- Emphasize practical skills and improvisation in teacher preparation
- Provide in-service professional development workshops on kit construction and implementation
- Partner with schools to support implementation and research

For Policymakers:

- Develop national policies promoting equitable access to practical science through low-cost approaches
- Establish quality assurance mechanisms for locally-developed equipment
- Allocate resources for teacher training, material support, and scaling initiatives
- Include guidance on low-cost approaches in curriculum documents
- Align assessment with conceptual understanding rather than specific apparatus

For Researchers:

- Conduct longitudinal studies examining sustained implementation and long-term impacts
- Expand low-cost laboratory development to other science subjects
- Investigate scaling challenges and strategies
- Examine equity impacts and mediating factors
- Develop and test innovations integrating low-cost physical kits with digital technologies

The inadequacy of laboratory facilities in developing country schools represents a significant barrier to quality science education and, ultimately, to scientific literacy and STEM workforce development critical for sustainable development. However, this study demonstrates that resource constraints need not be insurmountable barriers. Through creativity, collaboration, and commitment to contextualized solutions, educators can provide rich practical learning experiences even in challenging circumstances.

Low-cost chemistry kits represent not merely cost-cutting measures but pedagogical innovations with unique affordances. The requirement to improvise and adapt develops problem-solving capabilities and authentic understanding of scientific inquiry perhaps more effectively than following rigid protocols with perfect commercial apparatus. The use of everyday materials makes chemistry accessible and relevant, connecting school science to students' lives.

Most fundamentally, this research embodies a philosophy of possibility rather than deficit. Rather than cataloging what resource-limited schools lack, it demonstrates what they can achieve with ingenuity and appropriate support. This asset-based perspective, recognizing and building on existing capabilities and resources rather than lamenting deficiencies, offers a productive path forward for educational improvement in challenging contexts.

As Nigeria and other developing countries work toward achieving Sustainable Development Goal 4—ensuring inclusive, equitable quality education for all—low-cost laboratories offer practical, evidence-based strategies for extending quality science education to students in diverse circumstances. The kits developed and validated in this study provide concrete tools, the evidence demonstrates their effectiveness, and the documented experiences illuminate pathways for implementation and scaling.

The journey from recognition of equipment inadequacy to successful implementation of effective alternatives required sustained effort, collaboration among diverse stakeholders, willingness to experiment and learn from experience, and commitment to students' right to quality education regardless of their schools' resource levels. This journey continues, with opportunities for refinement, expansion, and scaling. We hope this research inspires and guides others traveling similar paths toward more equitable, accessible, effective science education.

References

[1]. Adekunle, A. A. (2017). Development and validation of low-cost distillation apparatus for secondary school chemistry. *Nigerian Journal of Science Education, 15*(2), 45–56.

[2]. Akpan, B. B. (2016). Improvisation in science teaching and learning: Electrochemistry experiments using local materials. *Journal of Chemical Education, 93*(2), 347–349. https://doi.org/10.1021/acs.jchemed.5b00652

[3]. Bekasiewicz, A., Pankiewicz, B., Wojcikowski, M., Klosowski, M., & Koziel, S. (2021). Application of open-hardware-based solutions for rapid transition from stationary to remote teaching model during pandemic. *IEEE Transactions on Education, 64*(3), 299–307. https://doi.org/10.1109/TE.2020.3035944

[4]. Berman, E. T., Hamidah, I., Mulyanti, B., & Setiawan, A. (2021). Low cost and portable laboratory kit for teaching and learning of air conditioning process in vocational education. *Journal of Technical Education and Training, 13*(3), 133–145. https://doi.org/10.30880/jtet.2021.13.03.013

[5]. Bima, M., Saputro, H., & Efendy, A. (2021). Virtual laboratory to support a practical learning of micro power generation in Indonesian vocational high schools. *Open Engineering, 11*(1), 508–518. https://doi.org/10.1515/eng-2021-0048

[6]. Borg, W. R., & Gall, M. D. (1983). *Educational research: An introduction* (4th ed.). Longman.

[7]. Bradley, J. D. (2001). UNESCO support for microscale chemistry in southern Africa. *Journal of Chemical Education, 78*(4), 462–463. https://doi.org/10.1021/ed078p462

[8]. Branch, R. M. (2009). *Instructional design: The ADDIE approach*. Springer.

[9]. Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology, 3*(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

[10]. Brown, J. S., Collins, A., & Duguid, P. (1989). Situated cognition and the culture of learning. *Educational Researcher, 18*(1), 32–42. https://doi.org/10.3102/0013189X018001032

[11]. Carlson, C., Peterson, G., & Day, D. (2020). Utilizing portable learning technologies to improve student engagement and retention. *IEEE Transactions on Education, 63*(1), 32–38. https://doi.org/10.1109/TE.2019.2941700

[12]. Cheung, D. (2009). Students' attitudes toward chemistry lessons: The interaction effect between grade level and gender. *Research in Science Education, 39*(1), 75–91. https://doi.org/10.1007/s11165-007-9075-4

[13]. Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Lawrence Erlbaum Associates.

[14]. Cook, T. D., & Campbell, D. T. (1979). *Quasi-experimentation: Design and analysis issues for field settings*. Houghton Mifflin.

[15]. Dale, E. (1969). *Audiovisual methods in teaching* (3rd ed.). Holt, Rinehart & Winston.

[16]. Domin, D. S. (1999). A review of laboratory instruction styles. *Journal of Chemical Education, 76*(4), 543–547. https://doi.org/10.1021/ed076p543

[17]. Driver, R., Asoko, H., Leach, J., Mortimer, E., & Scott, P. (1994). Constructing scientific knowledge in the classroom. *Educational Researcher, 23*(7), 5–12. https://doi.org/10.3102/0013189X023007005

[18]. Ekin, S., O'Hara, J. F., Turgut, E., Colston, N., & Young, J. L. (2021). A do-it-yourself (DIY) light wave sensing and communication project: Low-cost, portable, effective, and fun. *IEEE Transactions on Education, 64*(3), 205–212. https://doi.org/10.1109/TE.2020.3029543

[19]. Fajrin, S., & Hakim, D. L. (2022). Implementation of low-cost laboratory in education: A systematic literature review. *Jurnal Teknologi, Kejuruan, dan Pengajarannya, 45*(2), 123–132.

[20]. Federal Ministry of Education, Nigeria. (2018). *National survey of science education facilities in secondary schools*. Federal Ministry of Education.

[21]. Firdaus, M. L., Parlindungan, D., Sundaryono, A., Farid, M., Rahmidar, L., Maidartati, M., & Amir, H. (2019). Development of low-cost spectrophotometry laboratory practice based on digital image for analytical chemistry subject. In *Proceedings of the 1st Workshop on Multimedia Education, Learning, Assessment and its Implementation in Game and Gamification* (pp. 162–167). Atlantis Press. https://doi.org/10.2991/aes-18.2019.37

[22]. Gormally, C., Brickman, P., & Lutz, M. (2012). Developing a test of scientific literacy skills (TOSLS): Measuring undergraduates' evaluation of scientific information and arguments. *CBE—Life Sciences Education, 11*(4), 364–377. https://doi.org/10.1187/cbe.12-03-0026

[23]. Hofstein, A., & Lunetta, V. N. (2004). The laboratory in science education: Foundations for the twenty-first century. *Science Education, 88*(1), 28–54. https://doi.org/10.1002/sce.10106

[24]. Hofstein, A., & Mamlok-Naaman, R. (2007). The laboratory in science education: The state of the art. *Chemistry Education Research and Practice, 8*(2), 105–107. https://doi.org/10.1039/B7RP90003A

[25]. Huertas, J. I., Vázquez-Villegas, P., Díaz-Ramírez, J., & Tejeda, S. (2020). Low-cost and high-precision labs to promote active learning in online learning environments. In *2020 IEEE ANDESCON* (pp. 1–6). IEEE. https://doi.org/10.1109/ANDESCON50619.2020.9272050

[26]. Johnstone, A. H. (1991). Why is science difficult to learn? Things are seldom what they seem. *Journal of Computer Assisted Learning, 7*(2), 75–83. https://doi.org/10.1111/j.1365-2729.1991.tb00230.x

[27]. Johnstone, A. H., & Al-Shuaili, A. (2001). Learning in the laboratory: Some thoughts from the literature. *University Chemistry Education, 5*(2), 42–51.

[28]. Khaing, S. W., Nopparatjamjomras, S., Nopparatjamjomras, T. R., & Chitaree, R. (2018). Development of Arduino-based logic gate training kit. *Journal of Physics: Conference Series, 1144*(1), Article 012134. https://doi.org/10.1088/1742-6596/1144/1/012134

[29]. Kolb, D. A. (1984). *Experiential learning: Experience as the source of learning and development*. Prentice Hall.

[30]. Kurzweil, D., Macaulay, L., & Marcellas, K. (2023). The holy grail of developing partnerships for DL in military education: The keys to success. *Journal of Military Learning—Conference Edition 2023*, 73–83.

[31]. Lee, S. J., Jung, A., Park, J., & Yun, M. (2020). Cost-efficient hands-on learning design for computer organization course. In *2020 15th International Conference on Computer Science & Education (ICCSE)* (pp. 150–155). IEEE. https://doi.org/10.1109/ICCSE49874.2020.9201854

[32]. Lunetta, V. N., Hofstein, A., & Clough, M. P. (2007). Learning and teaching in the school science laboratory: An analysis of research, theory, and practice. In S. K. Abell & N. G. Lederman (Eds.), *Handbook of research on science education* (pp. 393–441). Lawrence Erlbaum Associates.

[33]. National Research Council. (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. National Academies Press.

[34]. Ofozoba, C. A., & Ofozoba, O. P. (2024). The military intervention in politics and its effects on the education system in Nigeria. *AJSTME, 10*(6), 1095–1102. https://www.ajstme.com.ng

[35]. Ogunniyi, M. B., Jegede, O. J., Ogawa, M., Yandila, C. D., & Oladele, F. K. (2014). *Improvisation in science teaching: The African experience*. UNESCO.

[36]. Okebukola, P. A. (2019). *The state of laboratory facilities in Nigerian secondary schools: A national survey*. Nigerian Academy of Education.

[37]. Olibie, E. I., & Akudolu, L. R. (2013). Toward a functional citizenship education curriculum in Nigerian colleges of education for sustainable development in the 21st century. *American International Journal of Contemporary Research, 3*(8), 95–102.

[38]. Ong, S. L., & Ling, J. P. W. (2020). Low-cost educational robotics car promotes STEM learning and 21st century skills. In *2020 IEEE International Conference on Teaching, Assessment, and Learning for Engineering (TALE)* (pp. 467–473). IEEE. https://doi.org/10.1109/TALE48869.2020.9368487

[39]. Osborne, J., Simon, S., & Collins, S. (2003). Attitudes towards science: A review of the literature and its implications. *International Journal of Science Education, 25*(9), 1049–1079. https://doi.org/10.1080/0950069032000032199

[40]. Piaget, J. (1970). *Science of education and the psychology of the child*. Viking Press.

[41]. Prieto, D., Aparicio, G., & Sotelo-Silveira, J. R. (2017). Cell migration analysis: A low-cost laboratory experiment for cell and developmental biology courses using keratocytes from fish scales. *Biochemistry and Molecular Biology Education, 45*(6), 475–482. https://doi.org/10.1002/bmb.21071

[42]. Ryan, R. M., & Deci, E. L. (2000). Self-determination theory and the facilitation of intrinsic motivation, social development, and well-being. *American Psychologist, 55*(1), 68–78. https://doi.org/10.1037/0003-066X.55.1.68

[43]. Sanfilippo, F., & Austreng, K. (2018). Enhancing teaching methods on embedded systems with project-based learning. In *2018 IEEE International Conference on Teaching, Assessment, and Learning for Engineering (TALE)* (pp. 169–176). IEEE. https://doi.org/10.1109/TALE.2018.8615221

[44]. Singh, M. M., Szafran, Z., & Pike, R. M. (2017). *Microscale chemistry and green chemistry: Complementary pedagogies*. Springer.

[45]. Slamnik-Kriještorac, N., den Langenbergh, R., Huybrechts, T., Gutierrez, S. M., Gil, M. C., & Marquez-Barja, J. M. (2021). Cloud-based virtual labs vs. low-cost physical labs: What engineering students think. In *2021 IEEE Global Engineering Education Conference (EDUCON)* (pp. 637–644). IEEE. https://doi.org/10.1109/EDUCON46332.2021.9454091

[46]. Uyanik, I., & Catalbas, B. (2018). A low-cost feedback control systems laboratory setup via Arduino-Simulink interface. *Computer Applications in Engineering Education, 26*(3), 718–726. https://doi.org/10.1002/cae.21917

[47]. Vavrus, F., & Bartlett, L. (2012). Comparative pedagogies and epistemological diversity: Social and materials contexts of teaching in Tanzania. *Comparative Education Review, 56*(4), 634–658. https://doi.org/10.1086/667395

[48]. Vygotsky, L. S. (1978). *Mind in society: The development of higher psychological processes*. Harvard University Press.

[49]. West African Examinations Council. (2020). *Chief examiners' report: Chemistry May/June WASSCE 2020*. WAEC.

[50]. Wong, W. K., Juwono, F. H., & Loh, W. N. (2020). Remote implementation of microcomputers laboratory practices: A case study. In *2020 Sixth International Conference on e-Learning (econf)* (pp. 214–218). IEEE. https://doi.org/10.1109/econf51404.2020.9385488

[51]. Xu, X., & Lewis, J. E. (2011). Refinement of a chemistry attitude measure for college students. *Journal of Chemical Education, 88*(5), 561–568. https://doi.org/10.1021/ed900071q