



IJSRIS
journal
ISSN: 2820-7157

★ INTERNATIONAL JOURNAL OF ★

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RECEIVED
17 August 2026



ACCEPTED
09 September 2026



PUBLISHED
1 October 2026



October 2026



Volume 5



Number 5



Pages from:
786 to 791

Design of low-cost experimental kits and their impact on academic performance in physics: a quasi-experimental study in Mbandaka (DRC)

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ABSTRACT

In many regions of sub-Saharan Africa, and particularly in the Province of Équateur in the Democratic Republic of the Congo, the teaching of physical sciences at secondary level

faces a structural shortage of resources. This article examines the effect of using low-cost teaching materials on the understanding of fundamental physics concepts among first-year students in the Scientific Stream (1^{ère} HS) in Mbandaka. Based on an inventory of local and recycled resources (PET bottles, syringes, bamboo, copper wire), the study assesses

learning progress using a quasi-experimental pre-test/post-test design with a control group ($N = 192$). The results show a highly significant statistical advantage for the experimental group (15.8/20 in the post-test; Hake's $g = 0.65$) compared with the control group, which followed a traditional lecture-based approach (11.5/20; $g = 0.25$; Mann-Whitney $U = 1,240.5$, $p < 0.001$). Direct hands-on engagement helps to reduce cognitive overload and promote lasting conceptual restructuring.

Keywords: *low-cost* equipment, experimental kits, academic performance, Hake's gain, secondary education, physics pedagogy.

1. Introduction

The teaching of physical sciences within the education system of the Democratic Republic of the Congo (DRC) faces an acute methodological and material crisis. In Équateur Province, and more specifically in the city of Mbandaka, almost all secondary schools lack functional laboratories and basic measuring instruments (Massamba, 2018). Faced with these structural shortages, teachers predominantly adopt a transmissive, theory-based and lecture-style approach to teaching. Physics, however – an empirical discipline based on the dialectic between observation, modelling and experimental validation – is reduced to a body of definitions to be memorised and mathematical equations disconnected from phenomenological reality (Johsua & Dupin, 1993).

This pedagogical shortcoming proves particularly detrimental to first-year students in the Scientific Humanities stream (1ère HS). This stage of study marks a major epistemological turning point: learners must break away from their initial experience (Bachelard, 1938) and move from a descriptive introduction to the life sciences to a structured and abstract formalisation of classical physics. Without the support of practical hands-on experiments, the transition to abstraction creates a sense of cognitive insecurity and helplessness among pupils, who relegate fundamental physical quantities to the status of inaccessible abstractions (Astolfi, 2008).

Faced with the prohibitive financial cost of imported laboratory equipment (dynamometers, optical benches, graduated glassware), the use of local resources and the creation of *low-cost* materials are emerging as a resilient and innovative pedagogical response (Kapakala, 2019; UNESCO, 2015). The central question of this research is as follows: *What is the effect of using low-cost teaching materials on the understanding of fundamental physics concepts among first-year students in the science stream in Mbandaka?*

To answer this, the research question is broken down into three specific objectives: (1) to identify reusable materials from the local environment that are applicable to the official curriculum; (2) to quantitatively assess, via a quasi-experimental design, the difference in performance between an experimental group (*low-cost* kits) and a control group (lecture-based method); (3) to measure the standardised learning gain (Hake's g) resulting from this approach.

2. Theoretical and conceptual framework

The analysis of the impact of manipulation on conceptualisation draws on three major theoretical frameworks in cognitive psychology and science education: Bruner's developmental theory of modes of representation (distinguishing between the enactive or action mode, the iconic or schema mode, and the symbolic or formula mode), Sweller's theory of cognitive load (which conceptualises the reduction of extrinsic load through the direct manipulation of familiar objects), as well as the 'island' investigation approach, conceived as a methodological adaptation of experimentation for overcrowded classrooms lacking dedicated laboratories.

2.1. The transition from the concrete to the abstract (Piaget, Bruner, Sweller)

According to Piaget's (1970) genetic psychology, the construction of logical-physical structures is based on actual action performed on objects. Bruner (1966) formalises this process through three modes of representing reality: *enactive* (based on direct manipulation), *iconic* (relying on images and diagrams) and *symbolic* (using mathematical language and equations). Optimal learning requires a sequential progression through these three stages. Skipping the enactive stage by eliminating practical work forces pupils to deal with complex symbols from the outset (e.g. $\rho = m/V$ or $P = F/S$), generating a major extrinsic cognitive overload that hinders understanding (Sweller, 1988).

2.2. The Inquiry-Based Science Education (IBSE) approach in overcrowded classrooms

Inquiry-based science education (IBSE) places the pupil at the centre of a cycle of problem-posing, hypothesis-forming and experimental verification (Minner et al., 2010). In schools in Mbandaka, characterised by overcrowded classes (50 to 70 pupils) with no practical work rooms, the traditional model of individual workbenches is impractical. The introduction of lightweight, *low-cost* kits, provided in sufficient numbers, enables the standard classroom to be reconfigured for cooperative learning in small micro-groups (clusters of 4 to 6

pupils), ensuring consistent cognitive engagement (Kapakala, 2019; UNESCO, 2015).

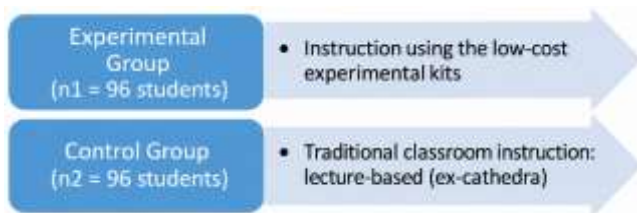
2.3. Balance between metrological rigour and simplicity of equipment

The use of homemade equipment raised the question of measurement accuracy. In physics education, a clear distinction is made between laboratory physics (high metrological precision) and first-year upper secondary school physics, where the priority is to validate the relationships between variables (Johsua & Dupin, 1993). To maintain scientific rigour, the engineering approach adopts a three-point strategy: the controlled reduction of friction, the calibration of homemade instruments using standard references (1 mL of water = 1 g) and the explicit inclusion of uncertainty calculations.

3. Methodology

3.1. Experimental design

The study is based on a quasi-experimental design with non-equivalent experimental and control groups, accompanied by pre-test and post-test assessments:



3.2. Sample

The sample comprises N = 192 Year 11 pupils from four secondary schools in Mbandaka, drawn from four school networks (state/state-subsidised and accredited private). The pupils were divided into two groups that were homogeneous in terms of group size and initial performance. The distribution is shown in the table below:

Table 1: Schools that benefited from teaching sessions using the low-cost experimental kits.

No.	School	Girls	Boys	Total
1	Frère ILOO Institute*	0	48	48
2	MPUTU Secondary School	25	23	48

3	Total	25	71	96
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In Table 1 above, it can be seen that the Institut Frère ILOO is attended exclusively by boys; it should be noted that this is a single-sex school for boys, which explains the absence of girls at this school.

Table 2: Schools that have benefited from traditional teaching sessions (ex-cathedra).

No.	School	Girls	Boys	Total
1	BAKUSU Institute	26	22	48
2	EDAP/ISP-MBANDAKA	24	24	48
3	Total	50	46	96

3.3. Data processing and indicators

Conceptual progress is assessed using **Hake's standardised gain (g)**:

$$g = \frac{\%Post - \%Pré}{100\% - \%Pré} \quad (1)$$

A gain $g \geq 0.70$ indicates a strong effect; $0.30 \leq g < 0.70$ indicates a moderate effect; and $g < 0.30$ indicates a weak effect. Comparative statistical analyses (Wilcoxon and Mann-Whitney tests) were carried out at a significance level of $\alpha = 0.05$.

4. Results

4.1. Inventory and design of low-cost experimental kits

An inventory of local resources available in the Mbandaka area has enabled the development of three experimental kits tailored to the three modules of the official 1st HS curriculum.

Table 3: Classification and design of low-cost experimental kits for the first year of upper secondary school.

Curriculum module	Local and recycled materials used	Handcrafted prototype designed	Physical phenomenon modelled / Equation validated
1. Measurements, densities & uncertainties	PET bottles (1.5L), graduated syringes (50mL), fine sand, fishing line, river water	Hydrostatic balance and handmade graduated cylinders	Density ($\rho = m/V$) and measurement of absolute uncertainties
2. Statics & study of forces	Springs salvaged from old mattresses and toys, bamboo sticks, wooden planks, metal hooks	Calibrated spring balance (0–5 N)	Hooke's law ($F = k\Delta x$) and the equilibrium of competing forces
3. Hydrostatics & pressure in liquids	Medical syringes (20 ml and 50 ml), flexible infusion tubes, PET bottles, vegetable oil	U-tube manometers, Archimedes' principal apparatus and hydraulic press	Pascal's principle and Archimedes' principle ($P_{\text{hydro}} = \rho \cdot g \cdot h$)

4.2. Comparative analysis of academic performance

Table 4 presents a comparative analysis of the scores obtained in the pre-test and post-test by the two groups of pupils.

Table 4: Comparison of academic performance between the experimental group and the control group.

Group	Sample size (n)	Pre-test average (/20)	Post-test mean (/20)	Gross gain (Δ)	Hake gain (g)	Interpretation of the effect (g)
Experimental group (<i>low-cost kits</i>)	96	9.18	15.82	+6.64	0.61	Higher-than-average effectiveness (close to the high threshold)
Control group (<i>lecture-based teaching</i>)	96	9.05	11.54	+2.49	0.23	Low efficacy

Total cohort	192	9.12	13.68	+4.56	0.42	Average overall effectiveness
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4.3 Hypothesis testing and statistical significance

The verification of the research hypotheses using non-parametric tests is summarised in Table 5.

Table 5: Summary of statistical comparison tests (Wilcoxon and Mann-Whitney).

Statistical comparison	Test applied	Statistic value	p-value	Effect size (r)	Statistical decision
Pre-test: Experimental vs Control	Mann-Whitney U	4,485.0	0.724	0.02	No significant difference (groups equivalent at baseline)
Post-test: Experimental vs Control	Mann-Whitney U	1240.5	< 0.001	0.74	Highly significant difference (Experimental group: higher)
Within the Experimental group (Pre/Post)	Wilcoxon Z	-8.421	< 0.001	0.86	Very strong improvement with <i>low-cost</i> kits
Intra-group control (Pre/Post)	Wilcoxon Z	-4.112	< 0.001	0.42	Moderate improvement with the lecture-based method

5. Discussion

The empirical results from this study confirm and extend observations made in science education regarding the importance of physical materials in the learning of physics (Minner et al., 2010). The highly significant statistical superiority of the experimental group in the post-test (15.82/20 versus 11.54/20; $p < 0.001$; $r = 0.74$) demonstrates that direct hands-on manipulation using homemade kits radically alters the assimilation of fundamental concepts, compared with traditional *lecture-based* teaching.

These findings corroborate Hake's (1998) work on the effectiveness of interactive engagement methods compared with passive methods. Whilst the control group, which received lecture-based teaching, remained in the low gain range ($g = 0.23$), the experimental group achieved a medium-

to-high standardised Hake gain ($g = 0.61$). This substantial difference can be explained theoretically in the light of **Sweller's (1988) cognitive load theory** and **Bruner's (1966) developmental model**. Indeed, in traditional lecture-based teaching, the absence of an inactive phase forces the learner to process mathematical abstractions and complex symbolic formalisms, thereby overloading their extrinsic working memory. Conversely, the use of *low-cost* kits rooted in everyday life (PET bottles, syringes, bamboo) provides immediate perceptual support that lightens this cognitive load and enables the concept to be firmly established before introducing the formal equation.

Furthermore, our findings align with those of Kapakala (2019) and Massamba (2018) regarding educational resilience in sub-Saharan Africa. Far from being mere inferior substitutes for laboratory equipment, these homemade devices prove to be remarkably effective in overcoming the obstacle of overcrowded classrooms through cooperative work in small groups. Finally, in response to sceptical criticism regarding the metrological accuracy of recycled instruments, our data support the position of Johsua and Dupin (1993): in first-year school physics, the focus is not on high-precision industrial metrology, but on the qualitative and semi-quantitative establishment of relationships of dependence between variables. The incorporation of measurement uncertainty transforms the imperfection of the equipment into a powerful heuristic tool for critical thinking.

6. Conclusion

The study aimed to analyse the impact of using low-cost teaching materials on the learning of physics in the first year of the Scientific Sciences stream in Mbandaka, by providing rigorous empirical answers to the three objectives set out in the introduction:

Regarding the first objective (inventory and design of teaching aids): The study demonstrated that it is entirely possible to make use of the immediate environment and recycled waste materials (PET bottles, syringes, bamboo, used springs) to design functional and robust prototypes. These teaching aids fit perfectly into the three key modules of the official 1ère HS curriculum (measurements and densities, statics and forces, hydrostatics and pressure).

Regarding the second objective (comparative quantitative assessment): The quasi-experimental pre-test/post-test design applied to the cohort of $N = 192$ pupils revealed a striking and statistically significant difference in performance. The experimental group, which benefited from the practical workshops, significantly outperformed the control group,

which was taught using the traditional lecture-based method (15.82/20 versus 11.54/20 in the post-test; Mann-Whitney $U = 1240.5$, $p < 0.001$).

Regarding the third objective (measurement of standardised learning gain): The calculation of Hake's gain enabled the didactic effectiveness of the approach to be objectively quantified, revealing a medium-to-high gain of $g = 0.61$ for the experimental group, thereby validating the relevance of enactive anchoring in overcoming cognitive overload.

In summary, this study demonstrates that the lack of conventional laboratory facilities is not an insurmountable obstacle to science education in the Democratic Republic of the Congo. The use of *low-cost* teaching aids offers school authorities and teachers an economical, environmentally friendly and highly effective alternative. Future research would benefit from exploring the extension of this approach to modules on optics and electrokinetics in order to consolidate the transition towards a contextualised approach to science teaching in sub-Saharan Africa.

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