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PET-Bottle Rocketry in Secondary Physics Education: An OBAFOG Project-Based Learning Experience Report

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ABSTRACT **Original Research Article**

This experience report investigated the implementation of Project-Based Learning (PBL) integrated into secondary Physics, Mathematics, and Chemistry education, contextualized within the Brazilian Rocketry Exhibition (OBAFOG). The pedagogical intervention engaged upper secondary students in an authentic, iterative engineering design cycle (*Design–Build–Test–Evaluate–Iterate*) focused on the fabrication and ballistic optimization of three successive PET-bottle rocket prototypes propelled by an aqueous acetic acid and sodium bicarbonate reaction. As the primary construction outcome, systematic aerodynamic and structural modifications—shifting the Center of Pressure aft via rigid planar fins, advancing the Center of Mass using ballasted nose fairings, and increasing the fuselage fineness ratio—resolved severe aerodynamic instabilities and increased mean horizontal ballistic range from 18.4±2.1" m" (Rocket 1) to 92.3±4.2" m" (Rocket 3). In terms of educational evidence, the collaborative diagnostic evaluation of early empirical failures fostered deep conceptual learning: students actively mobilized Newtonian mechanics, compressible fluid dynamics, and chemical stoichiometry to overcome technical bottlenecks, exhibiting heightened scientific reasoning, problem-solving autonomy, and teamwork. This study demonstrates that low-cost model rocketry serves as an effective experimental vehicle for authentic STEM engagement in secondary education.

Keywords: Physics Education, Project-Based Learning, PET-bottle Rocket, OBAFOG, STEM Education.

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Introduction

Educational institutions that adopt proactive and innovative pedagogical approaches cultivate learning environments that foster dialogue, critical inquiry, and authentic academic exchange between students and educators, enabling learners to identify their intellectual affinities and take ownership of their educational development (Bolina, et al., 2026). Within science and engineering education, this shift is closely tied to the transformation of student motivation. Rather than engaging in academic tasks primarily in pursuit of external validation or rote compliance, learners situated in problem-centered environments develop an autonomous orientation toward learning, deriving intrinsic satisfaction from intellectual competition, collaborative troubleshooting, and concrete problem-solving (Matias, et al., 2025).

Nevertheless, the implementation of active learning frameworks in secondary STEM education faces persistent structural and pedagogical challenges. Transitioning from traditional didactic instruction to student-centered inquiry often encounters resistance from learners accustomed to passive educational routines, which can constrain their initial willingness to navigate open-ended engineering design challenges. Furthermore, the absence of systematic pedagogical guidance, continuous professional development, and institutional support can impede educators from facilitating experimental learning effectively, particularly when teachers lack structured training in managing open inquiry or project risk. In addition, insufficient institutional planning and limited access to laboratory resources frequently restrict the sustained adoption of experiential learning strategies in formal school curricula (Pepino et al., 2024).

At the national level, scientific Olympiads serve as powerful catalysts for curricular innovation by providing structured, high-engagement platforms that bridge theoretical knowledge and empirical practice. With more than two decades of history, the Brazilian Astronomy and Astronautics Olympiad (OBA) have established itself as one of the country's preeminent scientific competitions. In 2007, OBA expanded its educational reach by establishing the Brazilian Rocketry Exhibition, currently known as OBAFOG (OBAFOG, 2025). Predominantly experimental in nature, OBAFOG challenges secondary students to design, construct, and launch rockets from ground-based platforms, primarily utilizing repurposed materials such as polyethylene terephthalate (PET) vessels, with the objective of maximizing horizontal ballistic range through collaborative team-based problem solving (OBAFOG, 2025).

Building on this national initiative, a private secondary school in Brasília, Brazil, integrates OBAFOG into its Physics, Mathematics, and Chemistry curriculum to promote active scientific engagement and foster practical engineering competencies among upper secondary students. Within this framework, students from Class 3B were presented with an authentic engineering challenge structured along an iterative pedagogical design cycle (*Design–Build–Test–Evaluate–Iterate*). By linking theoretical principles of Newtonian mechanics, compressible fluid dynamics, aerodynamic stability, and chemical stoichiometry to the physical construction and optimization of model rockets, this study reports on the qualitative implementation, ballistic performance outcomes, and formative learning evidence generated throughout this secondary school experience.

Method

Study Design and Pedagogical Approach

This study presents an experience report describing the implementation of a Project-Based Learning (PBL) activity integrated into the teaching of Physics and Mathematics in secondary education. The activity was developed in the context of the Brazilian Rocketry Exhibition (OBAFOG) and was conducted during April and May 2025 with students from Class 3B at a private secondary school in Brasília, Brazil.

The pedagogical intervention was structured around an authentic, open-ended challenge: the design, construction, testing, and improvement of a PET-bottle rocket capable of achieving measurable flight distance. The activity incorporated interdisciplinary STEM elements by connecting concepts from Physics, Mathematics, and Chemistry to the practical development and testing of the rockets. Rather than receiving the concepts exclusively through teacher-directed instruction, students were encouraged to apply previously acquired knowledge to the solution of a concrete engineering problem.

The project was organized according to an iterative engineering cycle consisting of design, construction, testing, evaluation, and redesign (Design–Build–Test–Evaluate–Iterate). This process was evidenced by the development of three successive rocket configurations (Rocket 1, Rocket 2, and Rocket 3), followed by modifications based on the problems identified during field testing. Thus, unsuccessful attempts were treated as opportunities for students to identify technical limitations, formulate explanations, and modify the design before subsequent tests.

Participants and Project Development

Interested students organized themselves into groups and independently developed and constructed their rocket projects. The project development process and its implementation were documented and submitted to the teacher responsible for the activity within a period of 30 days. Field tests were conducted in May 2025 by a team consisting of one third-year high-school student and three assistants.

Throughout the activity, students were required to apply concepts previously addressed in Physics and Mathematics classes, including force, motion, pressure, projectile motion, aerodynamics, and the relationship between launch angle and horizontal range. Chemical concepts related to the reaction between vinegar and sodium bicarbonate were also incorporated into the activity because this reaction generated the carbon dioxide used to pressurize the rocket system.

Formative Assessment and Evidence of Learning

Learning was monitored formatively throughout the project rather than through a standardized pre- and post-test. Before construction, the teacher identified students' prior understanding of concepts related to pressure, force, motion, and aerodynamics. During the construction process, the teacher observed how students mobilized these concepts to make design decisions and provided clarification when conceptual or technical difficulties arose. Following the field tests, students were encouraged to explain the differences in performance among the rocket configurations and to identify possible modifications that could improve subsequent performance.

The formative assessment therefore considered students' ability to relate theoretical concepts to practical decisions, interpret problems encountered during construction and testing, and explain the effects of structural, aerodynamic, and operational modifications on rocket performance. Particular attention was given to the application of Newton's

Third Law, pressure generation, thrust, aerodynamic stability, drag, mass distribution, and projectile motion.

Because the activity was conducted as an experience report, these observations were used descriptively to characterize students' engagement and application of knowledge rather than to estimate the effectiveness of the intervention through inferential statistical analysis. No standardized rubric, logbook, or pre- and post-intervention questionnaire was used; therefore, the educational observations reported in this study should be interpreted as qualitative and formative evidence derived from the implementation of the activity.

Mechanical Architecture and Materials Specification

To streamline the experimental setup and eliminate descriptive clutter in the main text, the physical infrastructure was divided into two modular subsystems: the ground launch platform and the aerodynamic vehicles. The launch base operated on an adjustable pneumatic-hydraulic manifold principle, providing ground stabilization and trajectory alignment via a 45° launch guide. System pressurization was continuously monitored using an analog Bourdon gauge, with a redundant quarter-turn ball valve for emergency venting (Figure 1).

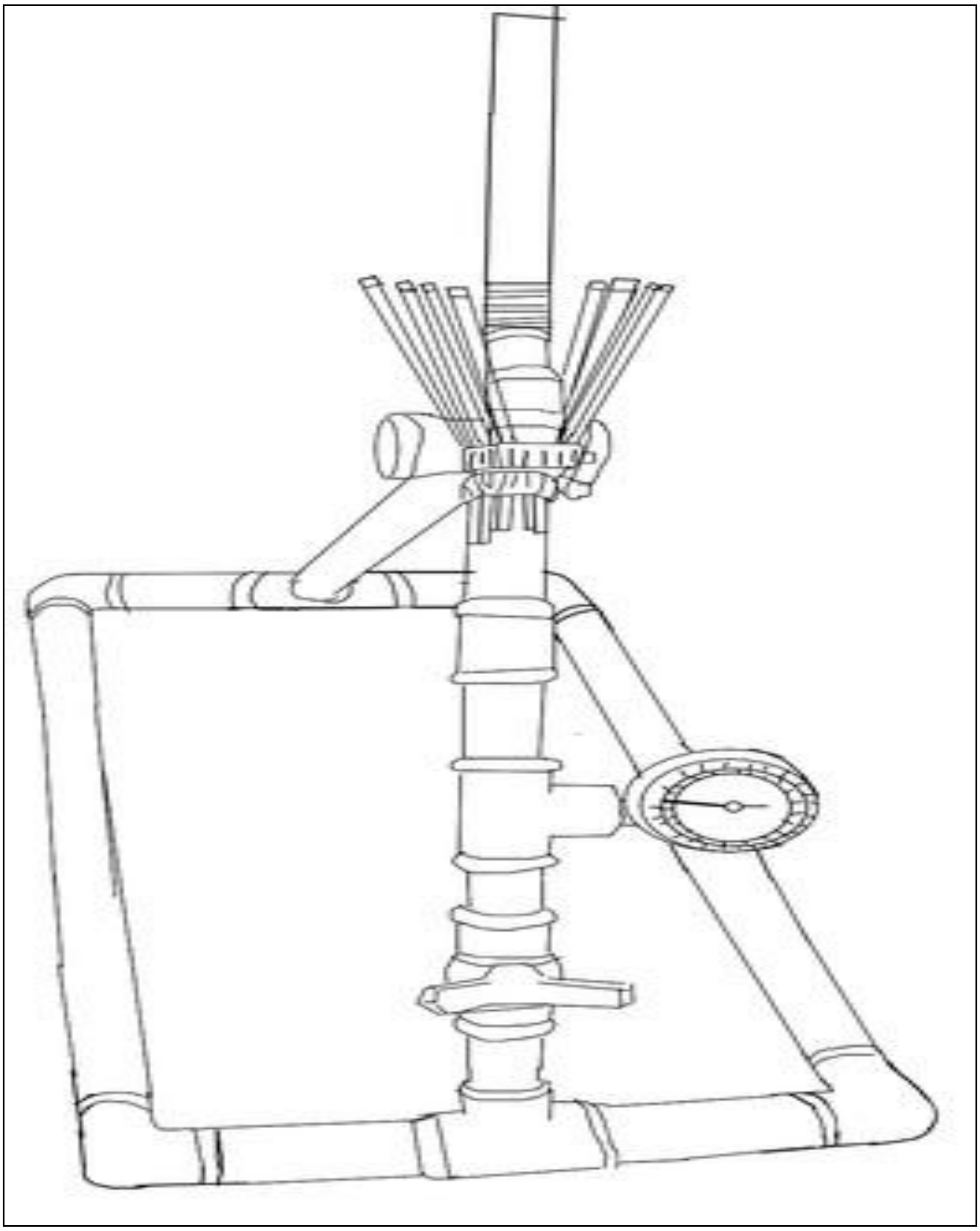

Figure 1. Schematic and assembled view of the pneumatic launch platform, highlighting the pressure gauge, safety depressurization valve, and 45° guide tube (Source: Authors).

The complete technical specifications, dimensions, and functional roles of all structural and hydraulic components are detailed in Table 1.

Table 1. Mechanical specifications and structural components of the experimental apparatus.

Subsystem	Component	Material & Dimensions	Functional Role
Launch Platform	Structural Frame	Rigid PVC pipe (Ø 25 mm: 5 × 45 cm; 5 × 10 cm; 3 × 6 cm; 1 × 28 cm)	Ground stability, structural chassis, and manifold support
	Launch Guide	Rigid PVC pipe (Ø 20 mm × 25 cm) & sleeve (Ø 40 mm × 5 cm)	Standardizes the 45° elevation angle and guides initial ascent
	Manifold Fittings	PVC 90° elbows (Ø 25 mm, n=4), equal tees (n=3), reducer bushing (25→20 mm), straight coupling (Ø 25 mm)	Hydraulic circuit routing and structural load distribution
	Pressure Monitoring	Analog Bourdon pressure gauge (0–300 psi [2068 kPa]) installed on a transition tee (25 mm to ½")	Real-time monitoring of pneumatic pressurization
	Pressure Relief	PVC ball valve (Ø 25 mm)	Emergency manual depressurization and drainage
	Mechanical Trigger	Zip-ties (n=12), worm-drive hose clamps (¾", n=2), remote release collar	Hermetic neck seal and remote mechanical pull-ring release
Rocket Vehicles	Pressure Vessel & Fuselage	2.0-L carbonated soft-drink PET bottles (n=4, burst threshold: >110 psi)	Propellant chamber and primary aerodynamic body
	Nose Cone (Fairing)	Repurposed high-density polyethylene (HDPE) shell ballasted with two-part epoxy putty	Aerodynamic penetration and forward mass distribution (adjusts Center of Mass)
	Empennage (Fins)	Rigid polymer sheet, cyanoacrylate adhesive (Tekbond 793®), BOPP tape	Aerodynamic stabilization (sets Center of Pressure aft of Center of Mass)

Source: Authors

Vehicle Prototypes and Control Variables

The iterative development progressed through three distinct vehicle configurations designed to test aerodynamic and structural variables while holding propellant chemistry and launch elevation constant.

Rocket 1 (baseline configuration): Consisted solely of the bare PET pressure vessel, serving as an unguided, non-aerodynamic control to establish baseline instability and thrust behavior.

Rocket 2 (stabilized aerodynamic configuration): Incorporated a parabolic HDPE fairing ballasted with epoxy putty at the apex and a set of three planar trapezoidal fins glued radially at 120° intervals around the base. This design established an aerodynamic restoring moment by shifting the Center of Pressure (CP) aft of the Center of Mass (CM).

Rocket 3 (extended rocket airframe configuration): Featured an extended dual-bottle architecture (sleeved tandem design) providing a higher fineness ratio and enlarged fin surface area, designed to optimize the glide path and minimize profile drag.

The operational parameters, mass properties, and performance metrics across configurations are systematically organized in Table 2.

Table 2. Experimental parameters, physical properties, and ballistic performance of rocket configurations.

Parameter / Variable	**Prototype 1 (Baseline)**	**Prototype 2 (Stabilized)**	**Prototype 3 (Extended)**	**Control Rationale**
Aerodynamic Configuration	Bare PET bottle; no nose cone or fins	Ballasted HDPE nose cone + 3 trapezoidal fins	Extended fuselage + ballasted nose cone + enlarged fins	Independent variable (aerodynamic stability & drag)
Propellant Volume Fraction	33% total volume (660 mL H_2O)	33% total volume (660 mL H_2O)	33% total volume (660 mL H_2O)	Fixed control variable (optimal reaction-mass ratio)
Dry Mass (m_{dry})	≈ 48 g	≈ 105 g	≈ 155 g	Structural mass excluding propellant
Wet Mass (m_{wet})	≈ 708 g	≈ 765 g	≈ 815 g	Total launch mass ($m_{dry} + m_{water}$)
Operating Pressure	60.0 ± 2.0 psi (413.7 kPa)	60.0 ± 2.0 psi (413.7 kPa)	60.0 ± 2.0 psi (413.7 kPa)	Fixed pneumatic baseline (safety threshold)
Launch Elevation Angle	45°	45°	45°	Fixed ballistic trajectory standard
Horizontal Range (X)	18.4 ± 2.1 m *(tumbling flight)*	64.8 ± 3.5 m *(parabolic arc)*	92.3 ± 4.2 m *(stable glide)*	Primary dependent outcome variable

Source: Authors

Biosafety Protocol and Risk Management (K-12 Compliance)

Because compressed pneumatic systems pose inherent kinetic and concussive hazards, a strict, institutional safety protocol was developed in compliance with laboratory guidelines for secondary education (K-12 STEM):

Structural margin of safety: Although standard carbonated beverage PET bottles exhibit nominal burst failure thresholds between 110 and 160 psi (758–1103 kPa), the experimental operating pressure was strictly capped at 60 psi (414 kPa). This established a structural safety factor ($\approx 2.5\times$), fully mitigating catastrophic ductile rupture of the pressure vessel.

Personal Protective Equipment (PPE): All students, assistants, and observing instructors within the launch perimeter were required to wear ANSI Z87.1-compliant impact-resistant safety goggles.

Safety exclusion zone and remote firing: Field activities adhered to a strict two-tier safety perimeter. The designated "firing line" was cleared to an azimuth of 180° downrange. The mechanical launch trigger was operated exclusively via a 15-meter non-elastic lanyard, ensuring that all participants remained well outside the potential blast radius during system pressurization and release.

Misfire and depressurization Standard Operating Procedure (SOP): In the event of a mechanical failure (such as a jammed trigger mechanism, neck seal leakage, or failure to launch under full pressure):

1. A mandatory 3-minute hold was enforced, during which no individual was permitted to approach the launch pad.
2. Following the observation period, the lead instructor alone approached the base along the aft sector (avoiding the longitudinal trajectory of the rocket).
3. Safe depressurization was achieved by manually opening the remote-accessible PVC relief ball valve on the ground manifold, completely evacuating internal pressure down to 0 psi gauge before any manual inspection or vehicle retrieval. Under no circumstances were students permitted to handle a pressurized, unreleased rocket.

Results

Ballistic Performance and Aerodynamic Optimization Across Prototypes

The empirical outcomes of the field trials demonstrate a direct relationship between vehicle structural architecture and ballistic efficiency. Across all configurations, the propellant volume fraction (33% H_2O equivalent to 660 mL) and initial pneumatic pressurization (60.0 ± 2.0 psi / 413.7 kPa) were held strictly constant, isolating the aerodynamic design and mass distribution as the governing independent variables. The quantitative ballistic performance and trajectory profiles are summarized in Table 3.

Table 3. Comparative experimental performance, aerodynamic characteristics, and flight dynamics across rocket prototypes.

Performance Parameter	Prototype 1 (Baseline)	Prototype 2 (Stabilized)	Prototype 3 (Extended rocket airframe)
Fuselage Architecture	Single 2.0-L PET vessel	Single 2.0-L PET + ballasted fairing	Dual-chamber sleeved tandem (extended length)
Empennage Configuration	Absent	3 planar trapezoidal fins (radial 120°)	3 enlarged-span trapezoidal fins
Dry Mass (m_{dry})	48.2 g	105.4 g	154.8 g
Wet Mass (m_{wet})	708.2 g	765.4 g	814.8 g
Mean Horizontal Range (X)	18.4 ± 2.1 m	64.8 ± 3.5 m	92.3 ± 4.2 m
Trajectory Morphology	Chaotic tumbling / early stall	Stable quasi-parabolic ballistic arc	High-apogee, extended glide trajectory
Primary Flight Limitation	Aerodynamic divergence (CP forward of CM)	Parasitic form drag and low fineness ratio	Residual mass penalty / trim sensitivity

Source: Authors

Prototype 1: Aerodynamic instability and loss of static margin

The baseline vehicle (Rocket 1), fabricated without stabilizing fins or forward fairing ballasting, exhibited severe flight path divergence immediately upon clearing the 45° launch guide. Lacking an aerodynamic restoring moment, the center of pressure (CP) was positioned ahead of the center of mass (CM), creating negative static stability (negative static margin). As the propellant mass rapidly evacuated, the instantaneous shift in CM toward the nozzle exacerbated the adverse pitching moment, inducing catastrophic tumbling and cross-flow separation. This dissipated the initial kinetic energy primarily into parasitic drag, yielding a mean horizontal range of only 18.4 ± 2.1 m.

Prototype 2: Correction of static margin and ballistic restoring moments

Prototype 2 was designed to correct the instability observed in Prototype 1 through two deliberate modifications: a ballasted high-density polyethylene (HDPE) nose cone and three trapezoidal fins affixed symmetrically around the aft perimeter.

1. The forward epoxy ballast effectively shifted the center of mass (CM) toward the apex.
2. The planar empennage shifted the center of pressure (CP) aft, achieving a positive static margin ($\Delta x_{CM-CP} > 1.0$ body caliber).

Field tests confirmed a stable, predictable quasi-parabolic trajectory, achieving a mean range of 64.8 ± 3.5 m, representing a 252% increase in flight distance over Prototype 1. The vehicle maintained directional alignment along its velocity vector throughout the thrust and coast phases.

Prototype 3: Rocket airframe extension, fineness ratio, and drag minimization

To explore the aerodynamic trade-offs between vehicle length, skin friction, and form drag, Prototype 3 incorporated an extended dual-bottle tandem fuselage and an enlarged fin surface area. The increased length improved the fuselage fineness ratio (L/D), effectively suppressing flow separation along the body and reducing base drag during the high-speed coasting phase. Prototype 3 achieved the greatest performance, attaining a mean horizontal range of 92.3 ± 4.2 m a 42.4% improvement over Prototype 2 and a 401% increase over the unguided baseline. The structural rigidity gained from the sleeved connection maintained axial alignment under peak pneumatic-hydraulic shear loads (Figure 2).

Figure 2. Distance achieved by Rocket 3. (Photo: Authors)

Mobilization of STEM Concepts and Pedagogical Impact

The iterative progression through these three prototypes served as an authentic vehicle for formative learning, demonstrating how hands-on engineering challenges bridge theoretical mechanics and empirical observation (Figure 3):

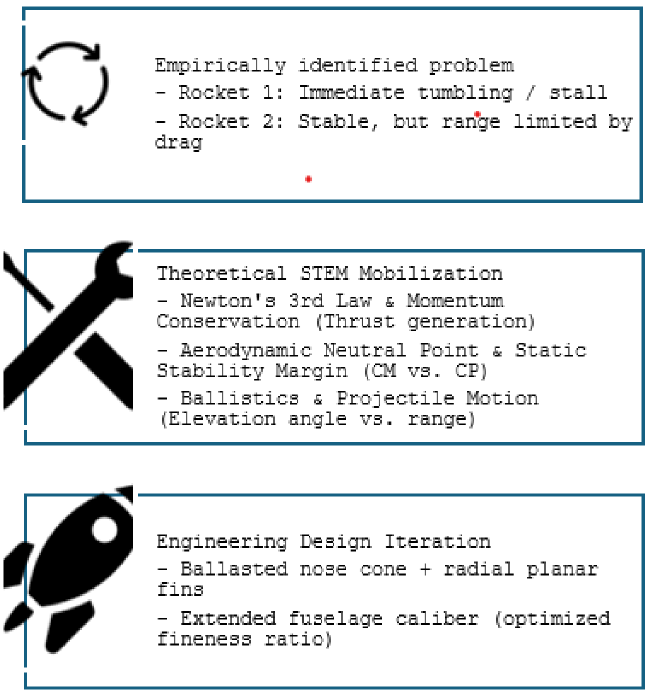

Figure 3. Schematic representation of the pedagogical engineering cycle (Design–Build–Test–Evaluate–Iterate**)** Source: Authors

Newtonian mechanics and propulsion: Students directly connected the duration and force of ejection (Newton's Third Law, $\vec{F}_{thrust} = \dot{m}\vec{v}_e$) to the propellant volume fraction, recognizing that air compression provided the stored potential energy, while water acted as the dense reaction mass maximizing impulse ($\Delta p = \int F\, dt$).

Aerodynamics and center of mass/pressure dynamics: The dramatic divergence of Rocket 1 transformed aerodynamic stability from an abstract formula into an intuitive spatial relationship. Students learned that aerodynamic stability requires the restoring aerodynamic lift forces generated by the fins (CP) to act *behind* the vehicle's pivot point (CM).

Formative assessment and engineering epistemology: Because failures were treated as critical diagnostic data rather than evaluative deficits, students engaged in sophisticated root-cause troubleshooting. Discourse shifted from qualitative observations ("it wobbled") to quantitative, engineering-grounded interpretations ("the rocket stalled due to negative static margin and lack of restoring torque").

Discussion

The present study demonstrated the feasibility of implementing an authentic engineering design challenge within secondary education through the construction, testing, and optimization of PET-bottle rockets using repurposed materials and a pressurized propulsion system. Framed within a Project-Based Learning (PBL) model, the intervention enabled students to transition from passive recipients of instruction to active investigators who mobilized fundamental principles of physics, chemistry, and mathematics to solve concrete operational problems. By confronting genuine empirical limitations during field trials, learners directly experienced the interplay between theoretical modeling and physical implementation, reinforcing active-learning concepts previously emphasized in secondary STEM education (Bolina et al., 2026; Matias, et al., 2025).

A central achievement of the activity was the practical application of Newtonian mechanics, fluid dynamics, and stoichiometry to explain rocket flight dynamics. Students observed Newton's Third Law in action, recognizing that the rapid expulsion of pressurized fluid through the nozzle generated an opposing reactive thrust force. Aerodynamic considerations were similarly integrated into structural decisions; the design of a conical fairing was understood not merely as an aesthetic choice, but as an aerodynamic profile intended to minimize skin-friction and form drag during high-velocity ascent. Concurrently, the addition of stabilizing fins arranged around the vehicle's base provided an aerodynamic restoring moment, counteracting pitch and yaw oscillations and preventing aerodynamic tumbling.

Chemical stoichiometry represented another critical dimension of the iterative learning process. The reaction between aqueous acetic acid (vinegar) and sodium bicarbonate was used to generate gaseous carbon dioxide to pressurize the vessel. During initial testing, students observed that non-stoichiometric reagent ratios severely compromised vehicle performance. Specifically, using a large excess of sodium bicarbonate relative to the limited concentration of acetic acid in commercial vinegar resulted in unreacted solute accumulating as a dense paste at the bottom of the bottle. This parasitic mass contributed substantial inertia without yielding additional pressurized gas, thereby diminishing the thrust-to-weight ratio and reducing propulsion efficiency. Engaging students in stoichiometric calculations to diagnose this failure mechanism transformed an apparent experimental mishap into a powerful pedagogical moment, demonstrating the practical relevance of quantitative chemical balancing in applied mechanics.

The trajectory variations recorded across prototype configurations corroborate previous findings in model rocketry literature. Fischer et al. (2020) demonstrated that incorporating a streamlined, ballasted nose cone not only reduces aerodynamic drag, but also concentrates mass in the forward section of the rocket, establishing a more favorable mass distribution that yields greater horizontal range. Furthermore, Toma et al. (2021) and Ribeiro et al. (2024) underscored that flight stability in water-and-air propelled rockets is critically governed by the relative positions of the Center of Mass (CM) and the Center of Pressure (CP). In agreement with these authors, the field observations in this study demonstrated that the baseline prototype, devoid of empennage and ballasted fairing, suffered catastrophic flight divergence due to a negative static margin, where the CP was positioned forward of the CM. Conversely, the addition of planar fins shifted the CP rearward while the nose ballast shifted the CM forward, creating a positive restoring moment that stabilized the trajectory and markedly increased flight distance, consistent with the structural adaptations described by Toma et al. (2021) and Abreu et al. (2018).

From an educational perspective, the progression across prototypes illustrates the capacity of PBL to enhance student autonomy and engagement. As Santos et al., (2022) notes, meaningful learning requires breaking away from traditional teacher-centered routines and empowering students to assume responsibility for constructing their knowledge. Confronted with suboptimal early launches, the students did not disengage; instead, they demonstrated persistence, cooperative troubleshooting, and systematic refinement of their prototypes. This iterative cycle of design, fabrication, failure analysis, and redesign aligns with the findings of Marques et al. (2021), who observed that active learning promotes open, participatory classroom environments that foster critical analysis and scientific reasoning.

Finally, the collaborative dynamics observed throughout the 30-day intervention reinforce the social dimension of STEM learning. As established by Preato et al. (2020) and Ribeiro et al. (2024), hands-on experimental rocketry challenges implemented in collaborative team structures facilitate sustained student motivation and authentic peer exchange. Ferreira et al. (2021) similarly demonstrated that active learning frameworks in secondary education are highly replicable and effective in fostering durable conceptual engagement. When coupled with institutional safety protocols and clear curricular integration (Pepino et al., 2024), authentic engineering projects such as the one described herein not only solidify foundational physics and chemistry concepts, but also nurture teamwork, self-efficacy, and an enduring interest in STEM disciplines.

Conclusion

This study demonstrated the feasibility and educational value of implementing a Project-Based Learning (PBL) rocketry challenge within secondary education, contextualized by the Brazilian Rocketry Exhibition (OBAFOG). The iterative engineering progression across three prototypes—transitioning from an unguided baseline to an aerodynamically optimized, extended-fuselage vehicle—yielded a notable performance gain, increasing mean horizontal range from 18.4 ± 2.1 m to 92.3 ± 4.2 m.

From a pedagogical perspective, confronting authentic empirical limitations (such as negative static margins and non-stoichiometric chemical propellant mixtures) transformed experimental failures into meaningful learning opportunities. Students actively mobilized interdisciplinary concepts spanning Newtonian mechanics, fluid dynamics, and chemical stoichiometry, cultivating critical thinking, teamwork, and problem-solving autonomy.

Future investigations should incorporate quasi-experimental designs utilizing standardized pre- and post-intervention instruments and validated conceptual rubrics to quantify cognitive learning gains and STEM self-efficacy more rigorously. From an experimental standpoint, subsequent research could integrate low-cost digital telemetry, such as onboard micro-altimeters and inertial measurement units (IMUs), combined with high-speed video tracking to extract dynamic flight parameters with enhanced analytical precision. Lastly, longitudinal studies are warranted to evaluate the lasting impact of such engineering design interventions on students' academic development, career affinities, and retention within STEM fields across diverse school contexts.

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