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Advancing Science Education through Project-Based Learning: An Analytical Framework of Practical Applications for Indian Secondary Schools in Resource-Constrained Settings

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Abstract

This study looks at how Project-Based Learning (PBL) can be used in real life to improve science education in Indian secondary schools with limited resources. By qualitatively analyzing 111 Hindi-language science projects that follow the National Curriculum Framework, it reviewed three projects that are representative: biodegradable waste decomposition, plant morphology, and rust formation for their design pedagogical content scientific and feasibility. Results show that these inexpensive investigations relevant to the context help develop core competencies effectively such as observation data analysis collaborative inquiry and reasoning based on evidence. By merging learning through experience with relevance to the community, PBL closes the gap between instruction in theory and real scientific practice, even under conditions of resource constraint. In addition, PBL has shown potential for issues of gender and social equity by fostering inclusive participation and contextualized engagement. The study ends with the statement that scaling PBL across schools would need coherent policy alignment, teacher professional development, and reform in assessment practices to take science learning out of rote memorization into reflective inquiry-driven socially responsive education.

Keywords: Project-Based Learning; Science Education; Inquiry Pedagogy; Educational Equity; India.

Introduction

Project-based learning is one way of facilitating learning through real-world problem-solving. It promotes an inquiry-based approach that develops critical thinking, creativity, and collaboration among students, as opposed to rote learning. Within the constraints imposed by required curricula and time-bound school science classes in India, the project-based approach could be a feasible alternative for enhancing student interest and understanding of scientific concepts. Current statistics present a compelling case for reform in science teaching. The 2021 National Achievement Survey found only 34% proficiency in secondary school students' abilities in science skills. Government school students spend less than two hours per month exposed to laboratories. Gupta's survey of 500 science teachers across five states revealed that 78% identified lack of practical exposure as the major barrier preventing their students from acquiring experimental skills. There is an urgent need for low-cost practical solutions that meet curricular requirements while operating under infrastructural constraints.

Gender disparities bring another dimension to challenges faced by education even as some recent trends are encouraging. Female enrollment in higher educational institutions offering STEM disciplines has seen a significant increase according to the Annual Report of All India Survey on Higher Education for years 2013-2019. Systemic barriers continue to impede access to equitable education opportunities for girls due to societal norms particularly in rural settings; research shows how female educational prospects can be adversely affected by traditional practices such as dowry systems. Broader societal norms encouraging women's participation in STEM fields will be influenced by better access to quality science education for women. The National Family Health Survey has brought out these connections revealing correlations between levels of educational attainment and health outcomes—higher educated women tend to use cleaner cooking fuels which means that science education affects community

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health standards. Regional studies like Parikh *et al*.'s work in Rajasthan further show how educational attainment affects household practices and choices regarding health particularly with regard to biofuel use and respiratory health.

This data makes it very clear that any reform in science education needs to be seen within the larger picture of social and economic conditions facing Indian communities. Experiential learning is the key element of Indian education system as per NCF 2005, for scientific temper and inquiry skills (NCERT, 2005). However, rote learning dominates classroom practices (Sharma, 2018). PBL can bridge this gap because it integrates laboratory and field-based activities as theoretical knowledge is complemented by practical experience. Modern pedagogical research supports such integration; Almarzuqi and Mat's (2024) framework indicates that blended learning approaches significantly enhance student engagement, understanding, and achievement in STEM subjects when digital tools are combined with face-to-face interactions. These approaches are very much applicable in resource-constrained environments where traditional laboratory infrastructure may not exist. PBL cannot be achieved through mere curriculum redesign but requires teacher preparation and community involvement. Thirumalai and Sarangapani (2025) emphasize developing communities of practice among teachers with the pedagogical support and resources needed to transform their teaching practices into project-based strategies effectively.

In project-based frameworks, teachers take on a facilitator role guiding students through inquiries and collaborative projects; this requires specific training plus continuous professional development (Krajcik & Shin, 2014). Also, experiential learning can be enhanced by service-learning initiatives that connect classroom activities to community needs. A study by Augusthian *et al.*, in 2022 on science camps for tribal communities shows how such approaches foster civic engagement within the community while addressing educational inequities faced by marginalized groups. Zahedi *et al.*, in 2021 also report similar service-learning projects in India which increase students' civic engagement as well as strengthen their ties to the community to make science education relevant as well as inclusive. All these different challenges—limited lab access, gender disparities, poor teacher training, and socio-economic barriers—underscore the necessity of inclusive educational practices embedded in PBL models if all students are to benefit equally from such reforms in education. We review the report on 111 PBL science projects for Indian students in Hindi, to verify the claims of PBL as a method of scientific inquiry in such educational contexts. This paper describes three projects, biodegradable and non-biodegradable materials, ground area and leaf area relationship in plants, and rust formation on iron that can be considered as PBL per se and what impacts they could have on student learning outcomes. Projects were chosen based on their compliance with NCERT curriculum standards, low resource requirements (less than ₹100 per student), and feasibility to complete within 3-4 weeks; hence these are good candidates for large scale adoption in schools having limited resources.

Theoretical Framework for Project-Based Learning in Indian Schools

Theoretical perspectives, sociocultural contexts, and implementation realities inform a sound theoretical basis for the role of Project-Based Learning (PBL) in science education reform in developing countries. Secondary schools in India have their challenges, making it necessary to consider how PBL can adjust itself to local circumstances without compromising quality and equity. The theoretical underpinnings of PBL are situated within constructivist theory. This theory posits that knowledge is constructed by the learner through active participation and engagement with real-world problems, rather than passively receiving information. Studies show that PBL achieves this by promoting collaboration, critical thinking, and the application of scientific concepts in practice (Mkhonta-Khoza, 2023; Turski, n.d.). The approach fits well into Vygotsky's social constructivism since learning happens through social interaction with cultural tools; thus, it relates more directly to collaborative classrooms (Barron *et al.*, 1998). However, resource constraints—often a major reality—make effective implementation difficult as they limit teachers from involving students actively in hands-on activities. Mkhonta-Khoza's (2023) study on Siswati teachers found that even though learners have a positive attitude toward activity-based learning due to resource constraints like inadequate teaching materials, the full potential of PBL cannot be realized.

Teachers are always caught up between the ideals of pedagogy and practical realities; this situation defines most parts of the educational landscape in developing countries. Sociocultural factors cannot be overlooked in the implementation of PBL, as they shape educational practices and outcomes. Burho *et al.* (2024) analyze resource constraints that effect opportunities to learn (OTL) for students; it is clearly seen that the teachers have a very high ability to change curricula and teaching methods in order to enhance learning within the limitations imposed by systems. Their work is particularly relevant in understanding how Indian

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educators might implement PBL even when there are infrastructure challenges. Černá *et al*. (2021) state that material resources are necessary for equitable access to learning opportunities, particularly for the economically disadvantaged groups. In India, where socioeconomic disparities are very much visible, ensuring that PBL implementation does not inadvertently widen achievement gaps is of utmost importance. The three projects studied—waste segregation, plant morphology, and rust formation—were selected intentionally since they required minimal resources (under ₹100 per student), making them applicable across varying socioeconomic backgrounds.

Digital technology integration can enhance the effectiveness of PBL even in resource-limited settings when it is implemented thoughtfully. Almarzuqi and Mat (2024) indicate that blended learning approaches combining traditional and digital tools significantly improve student engagement and learning outcomes in STEM subjects. However, substantial gaps exist between the available digital infrastructure and teachers' ability to use it effectively as revealed by Rawal's (2024) systematic review on digital competency among Indian school teachers. The study maps considerable variation across states, with urban schools generally better equipped than rural counterparts. This digital divide requires differentiated approaches to PBL implementation—some schools may be able to use digital tools for data collection and analysis while others will have to make do with traditional observational methods and manual recording. The flexibility of PBL as a pedagogical framework allows such adaptations without compromising core learning objectives Blumenfeld *et al*., 1991; sustaining student motivation in project-based environments depends more on meaningful problem framing and appropriate scaffolding than on technological sophistication—all achievable with minimal resources.

Teacher professional development is probably the most important factor in ensuring that PBL happens successfully. Research on problem-based learning in Indian medical education by Bijli and Shankarappa (2012) has shown that differences in students' backgrounds necessitate different training for teachers to enable them to move from teacher-centered to learner-centered learning. Their finding that "one size does not fit all" is also true for teacher training programs. Thirumalai and Sarangapani (2025) show how the mathematics teachers' professional learning community in India helps share the best practices and continues support for pedagogical innovations. Communities of practice are very useful for science teachers who want to implement PBL because they can use this forum to share projects developed locally, discuss problems with implementation, and work together to create assessment strategies suitable for project-based work. According to Krajcik and Shin (2014), teachers require both initial training in Project Based Learning principles and ongoing support as they gain experience in the much more complex role of facilitator than director of student learning, which is a huge departure from traditional instructional roles common to many Indian classrooms.

The theoretical framework we are using for our analysis also takes into account that PBL needs to address certain specific content knowledge while developing broader competencies. Inquiry-based learning in science education should balance procedural understanding (how to conduct investigations) with conceptual understanding (scientific principles and theories), according to Harlen (2013). The three projects that we discuss here do indeed demonstrate such a balance: students learn specific content about biodegradability (Kumar *et al*., 2017; Singh *et al*., 2019), plant morphology (Grime, 2001), and oxidation-reduction reactions (Davis, 2000) while simultaneously developing skills in observation, data collection, analysis, and communication. This dual focus on content and process is also supported by India's National Curriculum Framework which seeks the development of scientific temper along with mastery over subjects. PBL seeks to advance science education at Indian secondary schools through a theoretical framework that is itself broad enough to capture constructivist learning principles, takes into consideration sociocultural reality, pragmatism toward resource constraints, appropriateness of available technologies, and sustained teacher development. Such an approach will ensure that reform initiatives speak directly to challenges yet take full advantage of the potential inherent in PBL for transforming science learning from rote memorization into meaningful inquiry.

Research Design and Project Selection

This study does qualitative document analysis of project-based science activities for Indian secondary schools. A document in Hindi containing 111 science projects was reviewed regarding its pedagogical format, resources needed, and compatibility with inquiry-based learning principles as suggested by India's National Curriculum Framework (NCERT, 2005). Exemplar project selection used criteria from recent studies on effective science pedagogy in resource-constrained settings, particularly those pertaining to material accessibility, completion time frame, curriculum alignment, and student engagement potential (Pati, 2023).

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Document Analysis and Project Selection Criteria

The source document classifies projects into four types: practical work (hands-on construction or experimentation), cognitive tasks (observational learning), problem-solving (addressing specific scientific questions), and skill development (laboratory and analytical competencies). These categories reflect different dimensions of scientific literacy that students need to develop. From the 111 available projects spanning physics, chemistry, biology, and environmental science, we selected three exemplar projects for in-depth analysis: (1) Biodegradable and Non-Biodegradable Waste; (2) Plant Ground and Leaf Area Relationships; and (3) Rust Formation on Iron Nails. Selection criteria included clarity of instructions, replicability across diverse school settings at minimal cost (under ₹100 per student), feasibility of completion within 3-4 weeks as well as representation from different scientific domains and complexity levels. Pati's (2023) survey of science subject motivation among Indian secondary students informed our selection since this study reveals that practical relatable experiments have a significant influence on the student's interest toward pursuing a career in science education. The waste segregation project touches upon environmental concerns that are common to both urban and rural students; plant morphology relates to agriculture which is well known within most Indian households while rust formation depicts an everyday chemical process that can be seen at home.

Analytical Framework

Our analysis looked at each project from four angles: the pedagogical structure (how the project supports student learning), scientific content (the accuracy and depth of the concepts addressed), practical feasibility (what resources are needed and what challenges may arise in implementation), and alignment with constructivist learning principles. We assessed whether projects promote hypothesis generation, observation, data gathering, data analysis, and conclusion drawing—skills that Harlen (2013) lists as essential to scientific inquiry. The analysis also takes into account how projects might be adapted to different resource levels since schools in India function under widely varying material conditions. Zahedi *et al.*'s (2021) service-learning research shows that science projects relating classroom activities to community needs improve both learning outcomes and civic engagement; therefore, we assessed whether the chosen projects could be scaled up from individual learning to take on local environmental or social issues—thus transforming them into potential service-learning opportunities. For example, a waste segregation project could grow into a community awareness campaign while findings regarding rust prevention could be applied to construction practices in the area.

Project Descriptions and Expected Learning Outcomes

Each of these projects was chosen for its stated aim at teaching some specific scientific concept even as it simultaneously trains broader inquiry skills. The biodegradable waste project engages students with environmental chemistry and microbiology by having them set up controlled experiments, collect long-term quantitative data, and draw evidence-based conclusions about decomposition rates (Kumar *et al.*, 2017; Singh *et al.*, 2019). Students use materials that are typically found in Indian households and schools: vegetable peels, paper, plastic containers, and simple weights. The procedure involves taking samples of waste (5g each), separating them into biodegradable and non-biodegradable fractions, putting them inside perforated polythene bags, burying these bags in garden soil, and observing changes in weight over the next 3-4 weeks. Initial and final weights are recorded by students who then calculate percentage decomposition and relate their findings to problems regarding municipal waste management as reported for Indian cities. The project on plant morphology familiarizes students with botanical measurement and concepts of spatial ecology. Using common garden plants such as marigold, hibiscus, or coleus, students measure leaf dimensions, count total leaves and calculate total leaf area, plus ground area (canopy coverage). It requires very little equipment: string, scales for measuring, and graph paper—making it possible in schools without sophisticated laboratory facilities.

Students trace the outlines of leaves on graph paper to find out about area; they measure the height of the plant and dimensions of the canopy to calculate ratios between ground area and total leaf area. Doing this to three plants of the same species introduces fundamental ideas about sampling and variability. Grime's (2001) work on plant strategies is used theoretically to interpret results since students will find relationships among size of the plant, leaf area, and space requirements. The rust formation project teaches oxidation-reduction chemistry through a simple but scientifically rigorous experiment. Students learn what conditions are necessary for rust formation by placing cleaned iron nails in three different environments: one with distilled water (so both oxygen and moisture are present), another with boiled water covered with oil (preventing access to oxygen), and an environment containing anhydrous calcium chloride (which removes any moisture). After 3-4 days students observe patterns of rust formation or non-formation learning that corrosion requires both water plus oxygen. The experiment uses inexpensive materials that can be found

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in most school laboratories; it gives clear observable results that students can relate to everyday experiences of metal corrosion (Davis 2000). Students learn experimental design skills along with variable control skills and evidence-based reasoning while also learning practical applications such as how construction companies prevent rust when building bridges or manufacturers prevent it in cars.

Data Collection and Analysis Procedures

We provided a detailed description of the project process from start to finish, listed materials required with their estimated costs, time needed for various phases of implementation, and analyzed scientific concepts involved at different cognitive levels (recall, understanding application analysis). Tables were designed that would be used by students for making observations so as to do this systematically—a good scientific practice modeled. These tables would prompt quantitative measurements and qualitative observations plus any unexpected results or anomalies noted. Possible modifications for students having different learning needs or resource constraints were also considered since inclusive pedagogy requires flexibility in implementation (Augusthian *et al*., 2022). For instance, visually impaired students might use tactile methods to measure plant dimensions while schools lacking weighing equipment could use comparative methods for the waste decomposition project.

Project 1: Biodegradable and Non-Biodegradable Waste
Objective: To differentiate between biodegradable and non-biodegradable waste through decomposition experiments and assess the environmental implications. Materials: Vegetable peels, paper, plastic, glass, gloves, two plastic bags (10”×6”), nylon thread, spring balance, and a garden for burial. Procedure: Collect waste samples from the kitchen, garden, or market. Separate the samples into biodegradable (vegetable peels and paper) and non-biodegradable (plastic, glass, metal) categories. Each sample should weigh about 5g. Place the samples into two labeled perforated plastic bags: one for biodegradable samples (bag A) and one for non-biodegradable samples (bag B). Seal the bags using nylon thread. Weigh the sealed bags using a spring balance before burial. Dig a pit in the garden where the bags can be buried. After 3-4 weeks remove the bags from the pit. Clean the bags with soil without using water. Dry them under sunlight then reweigh them. Open both bags and observe which items decomposed or changed in any way. Record your observations in an observation table noting initial weight final weight and weight difference. Expected outcomes: The biodegradable samples will show significant weight loss due to microbial decomposition while non-biodegradable samples will remain unchanged indicating environmental persistence of synthetic materials contributing to pollution challenges documented in Indian cities (Kumar *et al*., 2017; Singh *et al*., 2019).

Project 2: Relationships Between Plant Ground Area and Leaf Area Objective: Establish relationships between a plant’s ground area (canopy coverage) and total leaf area exploring spatial adaptation strategies. Materials: Potted plants of marigold hibiscus coleus string measuring scale graph paper Procedure: Choose one potted plant species. Remove one representative leaf from it trace its outline onto graph paper to calculate area by counting 1 cm² squares of such paper then note total number of leaves on your chosen species calculate total leaf area as follows - area of one leaf multiplied by number of leaves; measure canopy width with string then breadth ground area equals width multiplied by breadth; measure height also count branches repeat these measurements on three different but same species ensure reliability calculate ratios ground to leaf areas analyze relationships between sizes of plants requirements spatially relating them back to ecological factors concerning adaptations described in literature about competition for resources among plants at different levels of growth potential within environments constrained by varying conditions. Expected outcomes: Bigger plants need more ground relative to leaf area reflecting spatial adaptation resource competition patterns described in plant ecology literature (Grime 2001). Project size influences ratio variations support hypotheses about growth strategies environmental constraints.

Project 3: Formation of Rust on Iron Nails Objective: To determine the conditions required for rust formation and suggest ways to prevent it. Materials: Three test tubes marked A, B, C; iron nails; distilled water; oil; anhydrous calcium chloride; corks; sandpaper. Method: Three test tubes are labeled A, B, and C. Test tube A is filled with distilled water. Test tube B is filled with boiled distilled water and topped with an oil layer. Test tube C is filled with anhydrous calcium chloride. Cleaned iron nails are used, and any existing rust is removed by rubbing the surface with sandpaper until it appears shiny and metallic. Place one nail in each of the three test tubes and seal the mouths of the test tubes with corks. After 3 to 4 days, observe and record any rust formation in the three different conditions. The expected results are that rust will form in A where both water and air are present, rust will be reduced in B where the oil layer prevents air contact, and no rust will be found in C where drying agents have removed moisture

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from the air. The experiment results show that iron corrosion occurs only when both water and air are present. This finding can be applied practically to prevent rust in construction and manufacturing industries (Davis, 2000).

Results and Discussion

Results

The three exemplar projects have clear pedagogical designs, resource requirements, and learning paths that together make them suitable for use in a variety of Indian secondary school contexts. Each project shows how PBL can enable the exploration of particular scientific content while developing broader inquiry competencies, even in resource-poor settings. The projects differ in their time requirements, material costs, and cognitive demands—thus offering teachers choices about which activities might be most appropriate to their own particular classroom situations. The biodegradable waste project needs the longest implementation time (3-4 weeks) but requires very little active student time—about 2 hours for setup and 1 hour for final observation and analysis. Material costs are kept under ₹50 per student since most materials (waste samples, plastic bags, thread) can be found at home. Environmental science concepts are addressed at multiple levels here: basic classification of materials; chemical decomposition processes; microbial activity; and more general ecological implications of waste management. Students will interact with quantitative data collection through weighing and calculating percentages that develop numeracy skills along with developing scientific understandings. A longer time frame also gives an opportunity to introduce students into longitudinal research methods teaching them patience and systematic observation—skills that are usually neglected in laboratory exercises concerned with immediate results.

The plant morphology project is much more flexible in terms of implementation since it requires only 2-3 hours of concentrated work which can be done in one long session or spread over several periods. Material costs are negligible (under ₹20 per student) since common garden plants and basic measuring equipment will be used. The scientific content here covers botany, geometry, and spatial ecology where students need to apply mathematical concepts (area calculation and ratio analysis) to biological questions. Built-in replication is part of the design since measurements from three plants will be taken thus introducing students to the idea of sample size and variability without actually having them learn about statistical methods formally. Teachers may extend this by having students compare different species or look at seasonal variation or even leaf area v/s photosynthetic capacity demonstrating how a simple initial design can scaffold ever more sophisticated inquiries. The rusting formation experiment is the most classic lab-based study among the three. It takes 3-4 days for rust to form but only 1-2 hours of student time. Material costs are ₹60-80 per student, which is a bit more than other projects because it needs test tubes, anhydrous calcium chloride, and distilled water—things that may have to be bought if not already in school labs. This project teaches basic chemistry ideas like oxidation-reduction reactions, environmental elements that change chemical actions, and experimental control through the design with three conditions. Students learn how to change variables in an organized way; this skill can be used in many different scientific fields.

The good clear results (whether rust is there or not) make this project very fitting for beginners in science experiments since it adds confidence before they go on to studies with less clear outcomes. Analyzing the projects against NCERT curriculum standards for Classes 9-10 shows a strong match with required learning goals across several scientific areas. The project on biodegradable waste speaks directly to topics in the curriculum such as "Natural Resources", "Our Environment", and "Management of Natural Resources", which are found in Class X science syllabi. It brings practical experience to abstract ideas like "biodegradability" and "environmental impact" through real measurable observations; students shift from just knowing definitions to understanding time and chemistry involved in decomposition. Further, it ties into larger curriculum themes on sustainable development and environmental citizenship that NCERT calls cross-cutting issues. The plant morphology project matches up with Class 9 material about "Tissues", "Diversity in Living Organisms," and Class 10 material about "Life Processes" especially photosynthesis and plant nutrition. By looking at leaf area related to ground coverage, students get into ideas about resource acquisition plus spatial competition which are parts of plant ecology. The math parts—area calculations, ratio figuring out, relationship analysis—tie into math curriculum goals around measurement, geometry, and data interpretation.

These interdisciplinary links show NCF's idea of breaking down fake subject boundaries for better overall understanding. Structured observation tables accompany each project, guiding students through the process of data collection while also modeling scientifically appropriate documentation formats. These tables serve two functions: they scaffold student learning by providing pre-structured organizational frameworks, and they record data in a form that can later be analyzed and interpreted. The tables differ in complexity according to the varying cognitive demands of the three projects. In the biodegradable waste project, for example, students use Table 1 to record their data regarding changes in mass over time during the experiment. The structure of the table requires students to calculate both absolute differences in mass and percentage decomposition, thus introducing proportional reasoning. It is expected that the biodegradable samples will lose between 40% and 60% of their initial mass, whereas non-biodegradable samples should not change at all (or only between 0–5%, which could as easily be due to measurements error or

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adhesion to soil). Students should note that biodegradable materials change color (become darker), get soft, and break up into smaller pieces; whereas non-biodegradable materials remain unchanged with respect to color, texture, and size/shape. Such qualitative observations add another dimension to quantitative measurement by teaching students that scientific evidence can come both from numbers and from descriptive observations.

Table 1. Data Recording Format for Biodegradable Waste Decomposition

Sample Type	Initial Weight (g)	Final Weight (g)	Weight Difference (g)	Percentage Decomposition (%)
Biodegradable (Sample A)	5.0	2.3	2.7	54%
Non-biodegradable (Sample B)	5.0	4.9	0.1	2%

The plant morphology project uses a more complex table accommodating multiple measurements across three plant specimens, as presented in Table 2. The table's structure encourages students to look for patterns across the three plants, calculate averages, and note ranges—basic statistical thinking without requiring formal statistical knowledge. Expected results show that ground area typically represents 50-70% of total leaf area for bushy plants like marigolds, reflecting the fact that leaves overlap when viewed from above. Taller plants with more branches generally show higher ratios, as vertical growth allows more efficient use of ground space. Students should notice that even plants of the same species show considerable variation in specific measurements, introducing concepts of biological variability and the importance of replication in scientific studies.

Table 2. Comparative Measurements of Plant Morphological Characteristics

Characteristic	Plant I	Plant II	Plant III	Average	Range
Number of Leaves	47	52	44	47.7	8
Area of One Leaf (cm^2)	12.5	11.8	13.2	12.5	1.4
Total Leaf Area (cm^2)	587.5	613.6	580.8	594.0	32.8
Plant Height (cm)	28	32	26	28.7	6
Number of Branches	8	9	7	8.0	2
Ground Area (cm^2)	314	380	298	330.7	82
Ground-to-Leaf Area Ratio	0.53	0.62	0.51	0.55	0.11

The rusting nail experiment described in this project provides an easier case involving observations that are qualitative and conclusions that are categorical. For example, students would use Table 3 to conclude that water and air are both necessary for rusting since only test tube A shows significant corrosion. From test tube B, they would learn that access to air reduces but does not eliminate rusting; from test tube C, they would determine that absence of moisture means there can be no rusting at all. They should observe that the nail in test tube A is covered with a reddish-brown substance (iron oxide), the nail in test tube B has changed color very slightly (indicating very slow oxidation), and the nail in test tube C remains shiny and metallic. With these observations, students can draw evidence-based conclusions about which chemical conditions promote corrosion rather than simply memorizing facts-this is genuine understanding based on their own experimental work.

Table 3. Observations of Rust Formation Under Different Environmental Conditions

Test Tube	Conditions	Observation After 3–4 Days	Rust Formation	Explanation
A	Distilled water (oxygen + moisture)	Brown coating on nail surface	Heavy	Both oxygen and water present
B	Boiled water + oil layer (limited oxygen)	Slight discoloration	Minimal	Oil barrier reduces oxygen contact
C	Anhydrous $CaCl_2$ (no moisture)	No visible change	None	Moisture removed by desiccant

The analysis of the projects' pedagogical structures identifies several design features that align with effective learning principles. All three projects begin with clear learning objectives stated in student-friendly language, which guide learners on what they will explore and why. The procedures are presented as a series of numbered steps, providing scaffolding for student work while maintaining a level of autonomy—students must make choices about sample selection, measurement techniques, and data recording. This blend of structure and freedom is essential to the success of PBL, especially with students unfamiliar with open-ended investigations. Each project integrates multiple forms of scientific practice: asking questions (What conditions cause rust?), planning investigations (How can we test this?), conducting procedures (following experimental protocols), collecting data (systematic measurement and observation), analyzing results (calculating percentages, comparing conditions), and drawing conclusions (interpreting patterns). This wide range of practices is consistent with current science education standards that promote

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scientific processes along with content knowledge. The projects also include opportunities for students to face and solve challenges—measurements that do not match perfectly, surprising observations, unclear results—experiences that build scientific resilience and problem-solving abilities typically missing from cookbook-style laboratory exercises.

A major factor in using PBL in Indian schools is the need for resources and how it can be expanded. Our cost study shows that all three projects are much lower than the ₹100 per student limit, so they can be financially possible even in government schools with low budgets for science. The biodegradable waste project costs about ₹30-50 per student (plastic bags ₹10, thread ₹5, waste samples free, access to weighing scale assumed available), the plant morphology project costs ₹10-20 per student (string ₹5, graph paper ₹10, plants available in school gardens), and the rust formation project costs ₹60-80 per student (test tubes ₹30 iron nails ₹10 calcium chloride ₹25 oil and distilled water 15). These costs assume that basic equipment like weighing scales and measuring instruments are available in schools which is a reasonable assumption for most secondary institutions. Apart from direct material costs infrastructure is required only minimally by the projects. The waste project needs only a small garden plot for burial; the plant project requires access to potted plants or a school garden; and the rust project can be conducted in a basic laboratory or even a classroom with adequate ventilation. None of them require specialized equipment, instruments dependent on electricity, or hazardous chemicals requiring special storage or disposal. This accessibility makes the projects suitable for rural schools that may lack sophisticated laboratory facilities addressing equity concerns around science education quality across urban-rural divides. Figure 1 shows how resources compare between three projects and their timelines of implementation to prove their accessibility over different school settings.

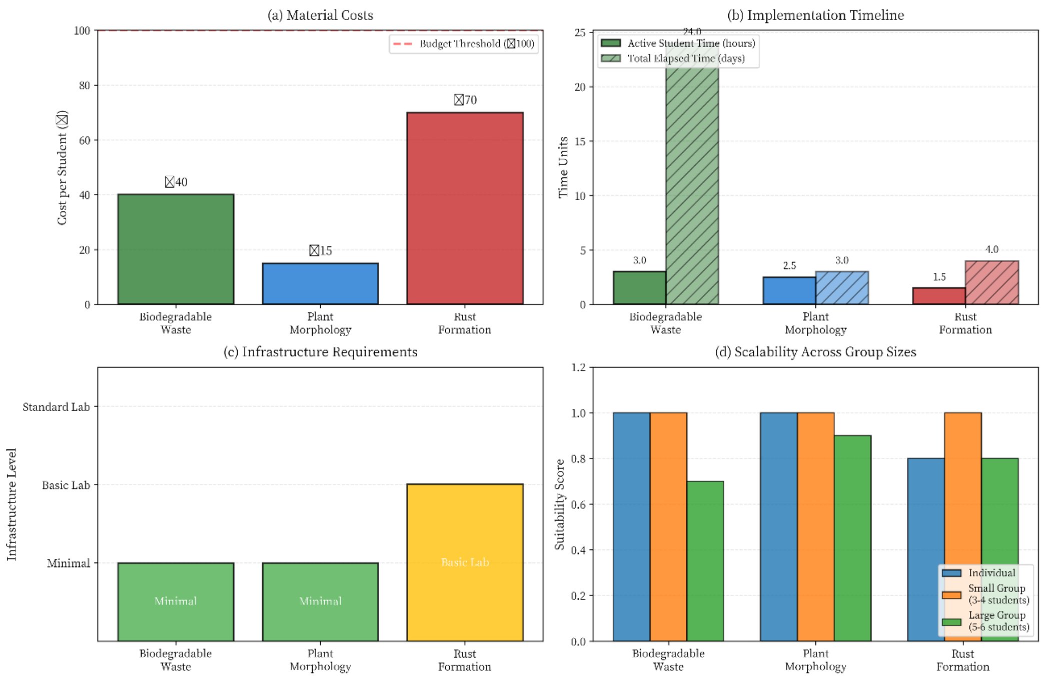

Figure 1. Comparative Resource Requirements and Implementation Timelines for Three PBL Projects

The scalability analysis shows that all three projects can be carried out by individual students, small groups of 3-4 students, or larger groups of 5-6 students depending on the availability of materials and the pedagogical goals in mind. Individual implementation would maximize hands-on experience at the expense of greater material costs and space requirements. Small group implementation is more resource-efficient but still allows for active participation since equipment can be shared among students who must ensure that all are involved in data collection and analysis. Larger groups further reduce costs but may result in some members being passive observers rather than active investigators. These are choices teachers will have to make based on their particular constraints and objectives. The projects present different levels of cognitive demand according to Bloom's taxonomy; that is to say, what kind of thinking skills they require from the students undertaking them. The rust formation project mostly involves lower levels of cognition: remembering chemical concepts, understanding oxidation processes, applying experimental procedures though it does involve analysis (comparing results across conditions) and evaluation (deciding which factors are necessary for rust). The plant morphology project requires higher-order thinking because it has students applying mathematical procedures to biological questions, analyzing relationships between variables, and synthesizing findings into coherent explanations of plant spatial strategies. The biodegradable waste project involves all cognitive levels from basic classification through synthesis

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of environmental implications and evaluation of waste management practices; this cognitive diversity allows teachers to select projects that fit their students' current capabilities while providing pathways toward more sophisticated thinking.

Discussion

The three model projects show that project-based learning could be made real in the Indian secondary school setting without losing scientific rigor and pedagogical richness. All three projects speak directly to the perennial issues of Indian science education — lack of hands-on exposure, theory-practice disconnection, poorly developed inquiry skills, and inequitable access to quality learning experiences. A critical review of these projects will show how even a carefully designed low-cost investigation can create an avenue for real scientific work in resource-poor settings. The main strength of these projects is that they are oriented toward real authentic scientific practice. Instead of just reproducing expected results, students get the opportunity to plan their own experiments and generate data and results that do not match textbook expectations—thus getting involved in the uncertainty and reasoning that is part of real scientific inquiry. For example, in the biodegradable-waste project, students must figure out how to collect data themselves and deal with non-standard rates of decomposition; this forces them to think about biological and environmental variability. In the plant-morphology and rust-formation projects as well, students change variables, see what happens, and explain what they find based on evidence. This type of effort develops analytical reasoning and scientific thinking far better than traditional verification exercises meant to confirm known results (Bell 2010; Thomas 2000).

These projects also have another very significant point: they relate directly to phenomena in the lives of students. Waste management, rusting of metals, and plant growth are all concrete phenomena that connect directly to local contexts. This relevance changes science from being an abstract academic subject into a practical tool for understanding real-world issues within one's community. Research has found that when science projects deal with real-life issues they improve not only conceptual understanding but also civic engagement (Blumenfeld *et al*., 1991; Zahedi *et al*., 2021). The biodegradable-waste study may even turn into service-learning via composting campaigns or community waste audits enabling students to make connections between environmental consciousness and scientific reasoning. These tasks also strike a good balance between structure and freedom. A clear order of steps gives support to students who may be new to open-ended questions, lessening doubt while still keeping focus. In this frame, however, students make real choices - picking materials, deciding how things should be measured, reading what they see. This mix of help and space for freedom backs ownership of learning gradually getting students ready for more independent study later on which is very useful in Indian classrooms where most students have little experience with self-directed learning(Sharma 2018). The project embodies the principles of cognitive and social constructivism. Knowledge is built through active participation, not passive reception. Group work enables learners to share different perspectives, discuss varying interpretations, and jointly create meaning. Collaborative interaction allows peer teaching when students have complementary strengths—math calculation versus careful observation, for example. These dynamics reflect Vygotsky's view of learning as a socially mediated process and fit well with the "communities of practice" model found in innovative teacher networks in India (Thirumalai & Sarangapani 2025).

Accessibility and equity are also fundamental to the project's design. All three projects use inexpensive and easily available materials—organic waste, garden plants, and iron nails—so that meaningful experimentation can occur even in schools with little lab infrastructure. This low-cost design helps reduce differences between urban and rural institutions and supports equitable access to quality science learning (Černá *et al*., 2021). However, accessibility extends beyond materials to teacher preparedness, institutional support, and time allocation; teachers need confidence in practical strategies for managing hands-on work while fostering inquiry rather than rote procedure. Large-scale professional development efforts are required for the transition from teacher-centered instruction to facilitative PBL where educators learn how to guide investigation effectively manage group dynamics and assess process-based learning effectively. Research by Bijli and Shankarappa (2012) shows that many Indian teachers have difficulty making these shifts under conditions of heterogeneity among student groups; sustained professional learning communities can take care of such needs because they provide shared space for reflection experimentation problem solving (Thirumalai & Sarangapani 2025). The three projects analyzed here provide actual entry points for teachers who want to experience inquiry-based pedagogy before trying their hands at more complex designs.

Time also is another big barrier. Teachers hurried by long syllabi often see project work as an extra burden without knowing how integrative PBL really is. A single good project like the one on biodegradable waste can address several curriculum objectives at once—environmental science, chemistry, and quantitative reasoning all come together in one activity (Krajcik & Shin, 2014). Instead of competing with syllabus coverage PBL promotes better mastery of core content through interconnected learning experiences. While the activities described here are meant for low-tech classrooms, they can easily blend in digital tools. Students can snap pictures of their setups, note changes over time, and use spreadsheets for calculations and graphs. These basic uses of tech build up digital skills and give visual proof for analysis. Blended learning—mixing face-to-face and online teaching—has been shown to boost motivation and learning in STEM subjects (Almarzuqi & Mat, 2024). But given the gaps in infrastructure and digital literacy in India (Rawal, 2024), tech should be used as an option not a must.

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Equity considerations also intersect with gender and social inclusion. Competitive science classrooms typically disadvantage girls and students from marginalized communities (Nandi *et al*., 2023; Hussain *et al*., 2023). The collaborative and contextualized nature of PBL can support more equitable participation if teachers monitor group dynamics to ensure balanced roles. Environmental management or plant growth projects may resonate with female students since these activities connect to familiar community contexts; however, teachers should frame such contexts as pathways into scientific thinking rather than feminine domains. Research with tribal learners further suggests that linking science to local knowledge systems—such as traditional waste management practices or indigenous plant taxonomy—can make science education more culturally relevant and inclusive (Augusthian *et al*., 2022). Assessment is an important part of PBL but it also becomes a hard task. Summative assessments are mostly about knowledge recall while PBL puts emphasis on inquiry processes, reasoning, and communication skills. The projects create different artifacts of learning data tables reports presentations videos that can be used for holistic assessment. Designing effective rubrics for these artifacts takes teacher expertise which is often missing from the current system (Sharma, 2018). Formative assessment during project work through peer review and teacher feedback can improve students' skills and understanding but is hard to implement in large classes. Peer assessment is one possible way to keep up the quality of feedback while also helping students develop reflective learning skills.

While they are promising, the three projects have some fundamental limitations that will inform future development directions. Each has dealt with relatively narrow, single-discipline problems producing predictable outcomes. Future projects should become increasingly open-ended and interdisciplinary as students and teachers gain confidence-involving chemistry, biology, mathematics, and social analysis so that they may better reflect the complexity of real-world problems (Zahedi *et al*., 2021). Similarly, while these projects promote classroom inquiry at a small scale, they could be expanded to community-based initiatives such as composting schemes or workshops on corrosion prevention or biodiversity surveys to increase students' awareness of scientific agency and social responsibility. Sustained teacher professional development is the key for long-term success. Teachers need strong content knowledge and flexible pedagogy as well as the ability to adapt PBL frameworks to local realities. Training has to go beyond short workshops into iterative cycles of practice, reflection, and peer exchange. When teachers themselves experience inquiry as learners, they internalize its principles more easily and become better equipped to facilitate investigations by their students. The three projects analyzed can serve as basic tools within such training programs-simple but conceptually rich examples that assist teachers in shifting from procedural instruction to genuine facilitation of inquiry. The results suggest that PBL has transformative potential for science education in India when it is based on constructivist pedagogy and contextual realities are taken into account. Low-cost contextually meaningful projects enable students to actively participate in scientific processes, develop higher-order thinking skills, and relate learning to society's relevance. However, this potential can only be realized through systematic support that includes curriculum design, assessment reform, and continuous investment in teacher capacity. It is only through such integrated efforts that PBL can move from an isolated classroom innovation into a sustainable model for equitable inquiry-driven science education across all schools in India.

Conclusion and Recommendations for Practice

Project-based learning is a realistic pedagogical approach for transforming science education in Indian secondary schools even under resource constraints. Our analysis of three exemplar projects decomposition of biodegradable waste measurement of plant morphology and investigation of rust formation demonstrates that authentic scientific inquiry can be conducted without sophisticated instruments or advanced laboratory infrastructure. Each project addresses a specific curriculum objective while simultaneously developing wider skills such as systematic observation data collection and analysis reasoning based on evidence collaborative problem-solving etc. The projects have costs ranging from ₹15 to ₹70 per student which makes them financially accessible across different school settings from well-funded urban institutions to government rural schools with minimal science budgets. In addition to material affordability the projects only require basic infrastructure garden space for the waste project common plants for the morphology investigation simple laboratory equipment for the rust experiment. This type of accessibility becomes very important in addressing equity issues within Indian science education wherein quality practical experiences have largely been confined to students from privileged schools.

The pedagogical design of these projects corresponds to the learning by doing principles which are constructivist and have been validated by research as highly effective for learning science. Students do not learn just through lectures or reading books; they learn by doing—by exploring phenomena, asking questions, determining methods for collecting data, observing systematically to find patterns, and drawing conclusions based on evidence. This is real scientific inquiry! The projects help bridge the gap between abstract notions of science with students' experiences and current issues in their communities so that motivation can be increased

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and science could be perceived as a tool for solving actual problems rather than an isolated academic discipline. Waste management, plant growth, and metal corrosion are all phenomena with which students continually interact every day of their lives; thus the investigations have immediate relevance and meaning to them. This kind of relevance could work particularly well when trying to engage those kids who might otherwise believe that science has absolutely nothing to do with their lives or dreams.

The projects also illustrated how PBL could achieve many curriculum objectives at once thereby answering the time constraint often cited by Indian teachers as a barrier to practical work. For example, in the biodegradable waste project classification of materials involves chemical decomposition processes, concepts about microbial activities from environmental science related to quantitative data analysis—all topics that would require several separate lessons under traditional instruction. By integrating these concepts into one single investigation PBL is more time-efficient than the fragmented approach of conventional science teaching. Project-based learning does not just require instructions to the teachers on how to conduct a project. It requires thorough professional training in content and pedagogy that would empower them to guide inquiry learning. Most science teachers in India have never had any personal experience with open-ended investigations; they were taught through lectures and memorization. The move from transmitter of knowledge to facilitator of inquiry is a fundamental change in practice which cannot be done through short workshops.

Professional development will involve doing projects themselves as learners, implementing projects with mentoring support in their classrooms, and ongoing participation in communities of practice where sharing student work helps troubleshoot problems and refine approaches collectively. Such sustained support becomes even more necessary under conditions of high-stakes examination culture within Indian secondary education whereby teachers are under pressure to prepare students for standardized tests that usually require factual recall rather than scientific reasoning and inquiry skills. Therefore, professional development needs to address how PBL can improve performance on examinations by creating deeper understanding more durable than rote memorization while also dealing with the larger issues of scientific literacy and critical thinking. Assessment is another area that needs special focus when implementing PBL. Traditional testing does not measure well some skills that projects can develop: observing, designing experiments, analyzing data, working with others, thinking scientifically, communicating. Teachers need help in developing and using assessment rubrics to judge these various aspects fairly and accurately. Rubrics should recognize that scientific inquiry involves both procedural skills (how one does investigations) as well as conceptual knowledge (principles and theories of science) so they assess students' development in both areas.

Formative assessment strategies are very useful because they enable teachers to provide feedback while students are still engaged in an investigation rather than after the fact when the task has been completed. However, effective implementation of formative assessment requires either small class sizes or additional teaching support—which resources are often lacking in Indian schools with 40-50 students per class. Peer assessment methods whereby students assess each other's work based on criteria provided by the teacher can somewhat relieve such limitations while also enhancing students' metacognitive skills and understanding of what constitutes good scientific work. Digital technologies can enhance both project implementation as well as assessment if resources allow; however, projects should be feasible without technology since infrastructure is not evenly distributed among Indian schools. These efforts are at best an entry point to the challenges of Indian science education and not a magic bullet. They show that PBL can be done in resource-poor settings but is limited to simple scientific challenges with clear and visible outcomes. Such structured projects can help students gain confidence and skills in project work, but eventually, teachers should introduce more open-ended investigations to better simulate real scientific research—studies where problems are not readily answerable and outcomes ambiguous, requiring considerable judgment from the student in method design and result interpretation. Moving from closed guides to open questions is critical for developing higher-order skills in identifying investigable questions and designing appropriate methods—skills that project work cannot develop fully.

Future project development should also focus more on interdisciplinary work because real-world scientific problems such as climate change or loss of biodiversity require knowledge from multiple traditional subjects. Projects integrating chemistry biology environmental science social science and math would better prepare students for such complex real-world issues while aligning with the National Curriculum Framework's vision of breaking down artificial divisions between subjects. Service-learning extensions are another area for enhancing the educational and social impact of projects. The biodegradable waste project could scale up from individual student learning to community-level initiatives on waste segregation and composting; students could carry out a waste audit in their schools or communities, develop composting systems, create educational materials for their families

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or neighbors, or engage with local government officials on waste management policies. Such extensions would deepen scientific understanding while nurturing students' sense of civic responsibility and agency—outcomes that increasingly are recognized as important educational goals alongside traditional academic achievement. The plant morphology project could extend to documenting biodiversity in a school or neighborhood investigating the relationship between plant diversity and environmental conditions or exploring connections with traditional agricultural knowledge.

The rust formation project could give back to local building practices or small-scale manufacturing with students developing rust prevention guides for artisans and construction workers. These service-learning transformations would make science education more socially relevant while also addressing equity concerns since students from economically disadvantaged backgrounds often have valuable community knowledge that can enrich scientific investigations when educators create space for such contributions. Gender equity is an issue that should not be pushed to the periphery in PBL; rather, it is an issue that needs to be mainstreamed. Research has shown that there are large gaps in Indian STEM education regarding female students who have good academic performance but are under-represented in science courses and careers. Traditional science teaching may emphasize competitive learning and individualistic styles of learning which disadvantage some females while collaborative socially-oriented learning appeals equally across genders. The three projects give excellent opportunities for group work and hence could create more inclusivity however teachers should be aware about group dynamics so that all students irrespective of gender, caste or any other social identities get their turn at the equipment, data collection and analysis.

Female students may particularly engage with the projects' links to real-world issues and community problems because research shows that they prefer learning science for social needs and practical problem solving. Such connections should serve as a point of entry into broader scientific thinking which breaks rather than reaffirms traditional gender boundaries by challenging stereotypes about what can constitute "appropriate" science topics for male and female students. Scaling PBL beyond classrooms to whole schools or districts requires a system support, not just professional development for teachers. School leaders need an understanding of why PBL works the way it does if they are to provide appropriate resources, time flexibility, and protection from the burden of over-examination pressure. District and state education officials must view PBL as real pedagogy deserving support instead of practical work being an add-on enrichment for those students who do the "real" academic work. Examination systems need to change so that they assess skills in reasoning scientifically and doing inquiry alongside factual knowledge so there is an incentive for teachers to do PBL rather than a penalty for time spent on practical investigations. Teacher education programs should prepare pre-service teachers with competencies in PBL instead of perpetuating traditional lecture-based approaches so that new teachers can enter the profession ready to facilitate inquiry-based learning. These systemic changes require sustained advocacy, policy development, resource allocation—challenges beyond individual educators' control but necessary for large scale transformation through PBL.

Questions that could not be answered from our analysis of project documents should be taken up by future research. Empirical studies in Indian schools on the impact of PBL on student learning outcomes would provide evidence about the effectiveness of projects in developing content knowledge and inquiry skills. Longitudinal studies tracking students exposed to PBL may indicate whether such approaches have an effect on long-term outcomes like science course-taking, career choices, and adult scientific literacy. Comparative studies of PBL implementation across different school contexts—urban versus rural, government versus private, states with varying educational policies—would explain how local conditions configure pedagogical possibilities and constraints. Teacher learning research might illuminate effective professional development models for supporting PBL implementation especially those that are sustainable and scalable under resource constraints for teacher support. Gender, caste, and socioeconomic factors in participation in PBL as well as its outcomes should be studied to ensure that inquiry-based approaches enhance rather than exacerbate existing educational inequities. Assessment practices rubrics and strategies identifying feasible methods to reliably evaluate PBL learning without overburdening teachers managing large classes with limited support.

The three projects that follow establish beyond a doubt that Project Based Learning can transform secondary school science education in India, not as a distant dream but as an achievable reality. Real scientific investigations are possible with very limited resources provided the projects are carefully designed to use locally available materials, satisfy curriculum objectives, relate to the experience of students, and allow proper scaffolding of learning. The full realization of PBL requires more than good designs for projects; it requires long-term professional development support for teachers, school contexts supportive of PBL implementation, reasonable class sizes, assessment tools aligned to PBL goals free from undue examination pressures and pathways for students

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from structured investigations towards increasingly open-ended inquiries that would help them develop their capacities for independent scientific thinking. Communities must be engaged as partners in learning science rather than passive recipients of knowledge generated by schools. Education systems must have policies and practices that value reasoning scientifically and inquiry as much as they do factual knowledge. These conditions can only be met through the collective action of educators, administrators, policymakers, researchers, and community members—an action that is worth taking because of the transformative potential that PBL holds for moving science education away from abstract content toward meaningful inquiry with real problems confronting students on complicated scientific and social issues when they become citizens or professionals in an increasingly interdependent world.

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