

Integrating Green Nanotechnology into Higher Education: A Pragmatic Framework for Enhancing Environmental Curricula and Sustainability in Libyan Institutions

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Abstract

This paper proposes a structured curriculum framework for integrating green nanotechnology into undergraduate science and engineering programs in Libyan higher education institutions. Drawing on the principles of green chemistry and sustainability-oriented pedagogy, the framework addresses a persistent tension in resource-constrained academic laboratories: the need to provide rigorous, hands-on scientific training while reducing reliance on hazardous reagents, energy-intensive procedures, and waste streams that many institutions are not equipped to manage safely (Anastas & Warner, 1998; O'Neil et al., 2021; UNESCO, 2017). The proposed model is organized around a three-phase laboratory sequence: preparation of aqueous plant extracts from locally available species, principally *Olea europaea* (olive) and *Punica granatum* (pomegranate); biogenic synthesis of metallic nanoparticles; and application of the resulting materials to the photocatalytic degradation of model organic dye pollutants. Each phase is linked to core undergraduate physical chemistry concepts, including reduction kinetics, surface capping, colloidal stability, and surface plasmon resonance (SPR) (Duan et al., 2015; Iravani, 2011; Nasrollahzadeh et al., 2019). By grounding these concepts in observable laboratory phenomena, the framework supports active, inquiry-based learning rather than passive instruction (Hmelo-Silver et al., 2007; Krajcik & Shin, 2014).

The paper is conceptual and design-based. It does not report experimental outcomes; instead, it offers a theoretically grounded model whose empirical validation is identified as a necessary next step. Its main strengths lie in low cost, alignment with local agricultural and environmental conditions, and the ability to connect scientific training with pressing environmental challenges, including dye-contaminated wastewater and sustainable materials development (Makhalanyane et al., 2020; Singh et al., 2018). The paper situates the proposal within the broader context of higher education reform in Libya and calls for systematic pilot implementation across multiple institutions, with attention to learning outcomes, protocol reproducibility, and waste reduction metrics.

Keywords: *green nanotechnology; higher education; Libya; sustainability education; green chemistry; plant-mediated synthesis; photocatalysis; inquiry-based learning*

1. Introduction

Universities in Libya face a dual, and not always easily reconcilable, responsibility. They are expected to modernize science curricula in response to global developments in materials science, environmental technology, and sustainable development, while also working within institutions constrained by limited budgets, uneven laboratory infrastructure, and shortages in consumables and technical support. Under such conditions, the gap between what is taught in

the classroom and what can be practiced safely in the laboratory can become uncomfortably wide.

Green nanotechnology offers a promising route through this difficulty. As an applied branch of materials science, it emphasizes the synthesis and use of nanoscale materials through methods that reduce toxic inputs, lower energy demand, and generate manageable waste (Kharissova et al., 2019; Nasrollahzadeh et al., 2019). Plant-mediated, or biogenic, nanoparticle synthesis has received particular attention because it combines controlled chemistry with unusual experimental accessibility: reactions can often be conducted in water, under mild conditions, and with botanical materials that are inexpensive and locally available (Iravani, 2011; Jadoun et al., 2021; Shankar et al., 2004).

For higher education institutions operating under resource constraints, these characteristics translate into clear pedagogical advantages. Laboratory activities based on plant-mediated nanoparticle synthesis can be implemented without specialist nanofabrication equipment, can reduce chemical hazards, and can produce visible results that students readily engage with. When the activity is supported by appropriate conceptual scaffolding, it can become a vehicle for teaching nucleation, surface chemistry, colloidal behavior, optical properties, and catalytic function at the nanoscale (Hingant & Albe, 2010; Laherto, 2020; Sweeney et al., 2006).

The present paper therefore proposes a structured curriculum framework tailored to the institutional and environmental realities of Libyan universities. Rather than presenting green synthesis as a generic educational trend, the framework is designed around plant species available in the Libyan agricultural landscape, environmental problems relevant to Libyan graduates, and the operational limits of many university teaching laboratories. In this sense, the paper contributes both to nanotechnology education and to context-sensitive curriculum reform.

1.1 Contribution Statement

This paper makes three contributions to the existing literature. First, it develops an explicit mapping between biogenic nanoparticle synthesis mechanisms and undergraduate physical chemistry learning objectives, a connection that previous nanotechnology education studies have often treated only in broad terms (Çelik & Çelik, 2024; Laherto, 2020). Second, it reframes biological variability in plant extracts as a pedagogical resource rather than merely a methodological weakness. Instead of treating extract inconsistency only as a source of error, the framework uses it to teach experimental design, control of variables, and interpretation of imperfect data. Third, it situates the model within Libyan higher education, offering a locally grounded alternative to imported green chemistry curriculum packages (Eilks & Hofstein, 2015; Grieger et al., 2022).

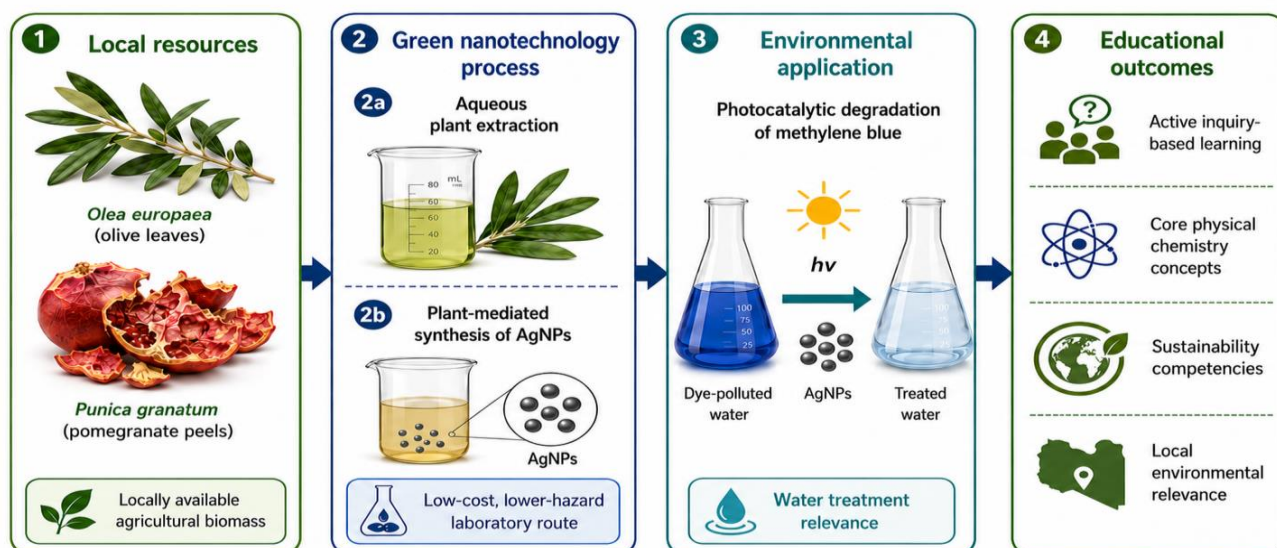


Figure 1. Conceptual framework for integrating green nanotechnology into Libyan higher education

2. Research Problem

Laboratory instruction in many undergraduate science programs continues to rely on conventional protocols that were designed before sustainability and chemical safety became central expectations in science education. Students may still be asked to use hazardous reducing agents, generate chemical waste that is difficult to treat, or perform experiments whose conceptual goals could be achieved through safer and cheaper methods (Mack et al., 2008; O'Neil et al., 2021; Timmer et al., 2018).

This issue is particularly serious in resource-constrained systems. Where infrastructure for hazardous waste management is weak, reagent-intensive laboratory teaching is not simply an old habit; it becomes a safety and environmental liability. A green chemistry curriculum, in this setting, is not a luxury or a decorative addition to the syllabus. It is a practical response to laboratory realities and a way of aligning scientific education with responsible practice (Anastas & Warner, 1998; Armstrong et al., 2018; Zhang et al., 2023).

A second dimension of the problem concerns relevance. Many students encounter environmental issues such as wastewater contamination, unmanaged solid waste, and degradation of agricultural resources in their own communities, yet their laboratory training often treats chemistry as abstract and disconnected from these realities. This separation weakens both motivation and environmental literacy. Education for sustainable development argues that students should not only learn about sustainability, but also practice the forms of reasoning and problem-solving that sustainability requires (Brundiers et al., 2021; Rieckmann, 2018; UNESCO, 2017; Wiek et al., 2011).

The central question addressed by this paper is therefore whether a component of undergraduate physical chemistry laboratory instruction can be redesigned to reduce chemical hazard and waste, strengthen conceptual learning, and connect students' scientific training to locally relevant environmental challenges. The proposed framework is a theoretically grounded answer to that question and is intended to serve as a basis for pilot implementation and evaluation.

3. Theoretical Framework

3.1 Chemical Foundations: Biogenic Nanoparticle Synthesis

The synthesis of metallic nanoparticles through plant extract-mediated reduction is well established and has been applied to silver, gold, zinc oxide, copper, and other nanoparticle systems (Duan et al., 2015; Irvani, 2011; Jadoun et al., 2021; Singh et al., 2018). In this process, plant secondary metabolites, especially phenolics, flavonoids, terpenoids, alkaloids,

and organic acids, can act as both reducing agents and surface-stabilizing, or capping, agents during the conversion of metal ions into nanoscale particles (Mustapha et al., 2022; Vanlalveni et al., 2021).

At the mechanistic level, the reaction can be understood as a redox process in which electron-rich functional groups within phytochemicals reduce solvated metal ions, such as Ag^+ , to lower oxidation states that then undergo nucleation and growth. The rate and outcome of this process are influenced by temperature, pH, metal salt concentration, extract concentration, incubation time, and the phytochemical composition of the plant material (Bergal et al., 2022; Shahzadi et al., 2025; Vanlalveni et al., 2021). Once nuclei form, adsorbed biomolecules can limit aggregation through steric and electrostatic stabilization, producing colloids whose properties depend on synthesis conditions.

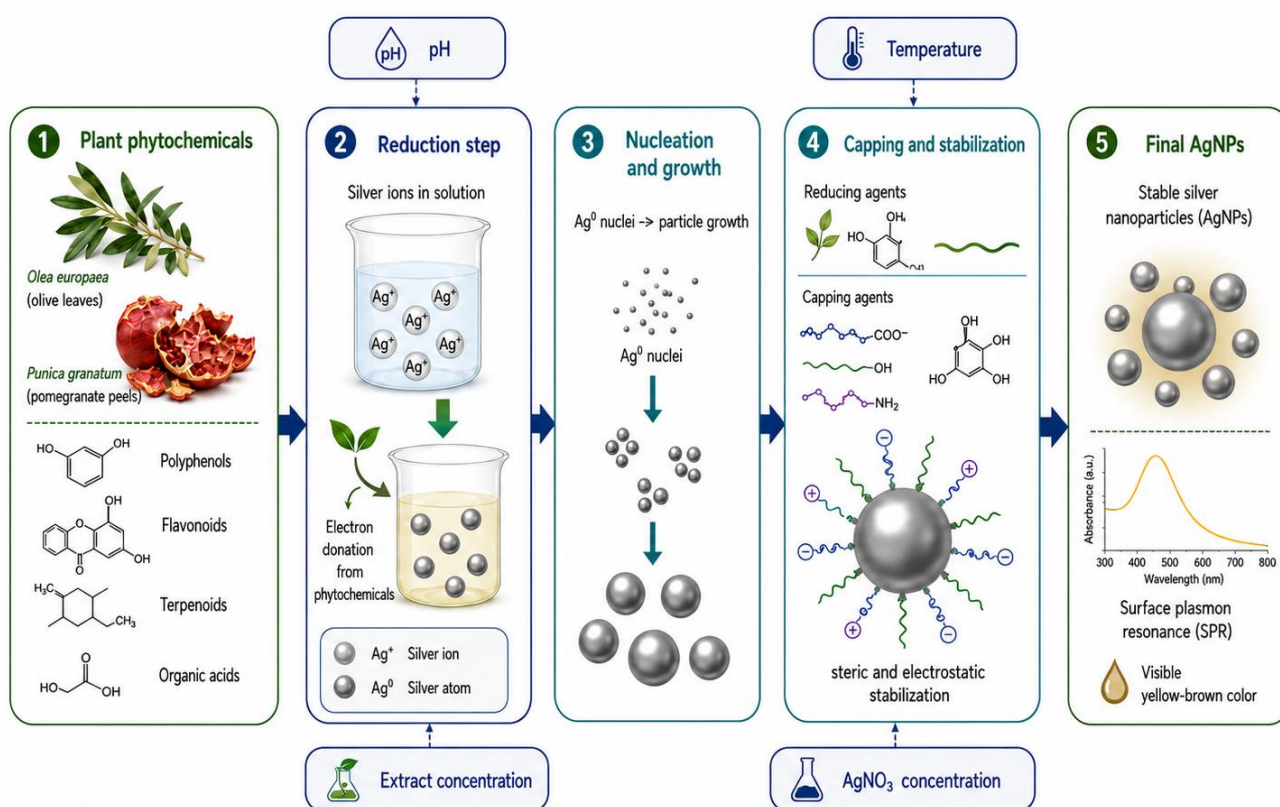


Figure 2. Mechanistic representation of plant-mediated silver nanoparticle synthesis

The visible color change associated with silver nanoparticle formation is usually attributed to surface plasmon resonance (SPR), the collective oscillation of conduction-band electrons at the nanoparticle surface in response to light. For silver nanoparticles, an SPR absorption band commonly appears in the visible region, often near 400-450 nm, although the precise position depends on particle size, shape, surface chemistry, and the surrounding medium (Alotaibi et al., 2024; Nasrollahzadeh et al., 2019). UV-Vis spectrophotometry therefore offers a practical, non-destructive method for students to monitor nanoparticle formation and discuss structure-property relationships.

In photocatalytic applications, green-synthesized nanoparticles can contribute to the degradation of organic dyes by enhancing light absorption, promoting charge transfer, or supporting the formation of reactive oxygen species that attack dye molecules (Makhalyane et al., 2020; Singh et al., 2018). Studies using plant-derived silver nanoparticles, including systems based on olive leaf and pomegranate peel extracts, have shown activity toward model

dyes such as methylene blue, making this application particularly suitable for an educational framework that connects nanochemistry with environmental remediation (Alotaibi et al., 2024; Joshi et al., 2018).

3.2 Pedagogical Foundations: Inquiry-Based and Sustainability-Oriented Learning

The educational rationale for the framework draws on two complementary traditions: inquiry-based learning and education for sustainable development. Inquiry-based learning places students in the role of investigators rather than passive recipients of predetermined results. In laboratory settings, such approaches can improve conceptual understanding, motivation, and problem-solving capacity, especially when students are asked to interpret results that are uncertain or variable rather than merely confirm textbook expectations (Hmelo-Silver et al., 2007; Krajcik & Shin, 2014).

Green nanotechnology experiments are well suited to inquiry-based teaching. The formation of nanoparticles produces a visible and memorable color change, while small procedural differences can affect colloidal stability, spectral response, and catalytic behavior. Instead of hiding this variability, instructors can use it to prompt authentic scientific questions: Why did one group obtain a darker colloid? Why did another group record a broader SPR band? Which variables were controlled, and which were not? These questions mirror the interpretive work of real experimental science (Blonder & Sakhini, 2015; Çelik & Çelik, 2024; Laherto, 2020).

Education for sustainable development extends this rationale by emphasizing systems thinking, anticipatory thinking, normative reasoning, collaboration, and integrated problem-solving (Brundiers et al., 2021; Rieckmann, 2018; UNESCO, 2017; Wiek et al., 2011). A laboratory sequence that uses plant waste or low-value agricultural materials to synthesize functional nanomaterials for dye degradation does more than illustrate sustainability. It gives students a concrete experience of how scientific design choices can reduce hazard, valorize local biomass, and address environmental problems. This experiential dimension is consistent with research showing that transformative and project-based approaches can produce stronger sustainability learning than information-only instruction (Leal Filho et al., 2018; Zhang et al., 2023).

4. Proposed Curriculum Framework: Design and Protocol

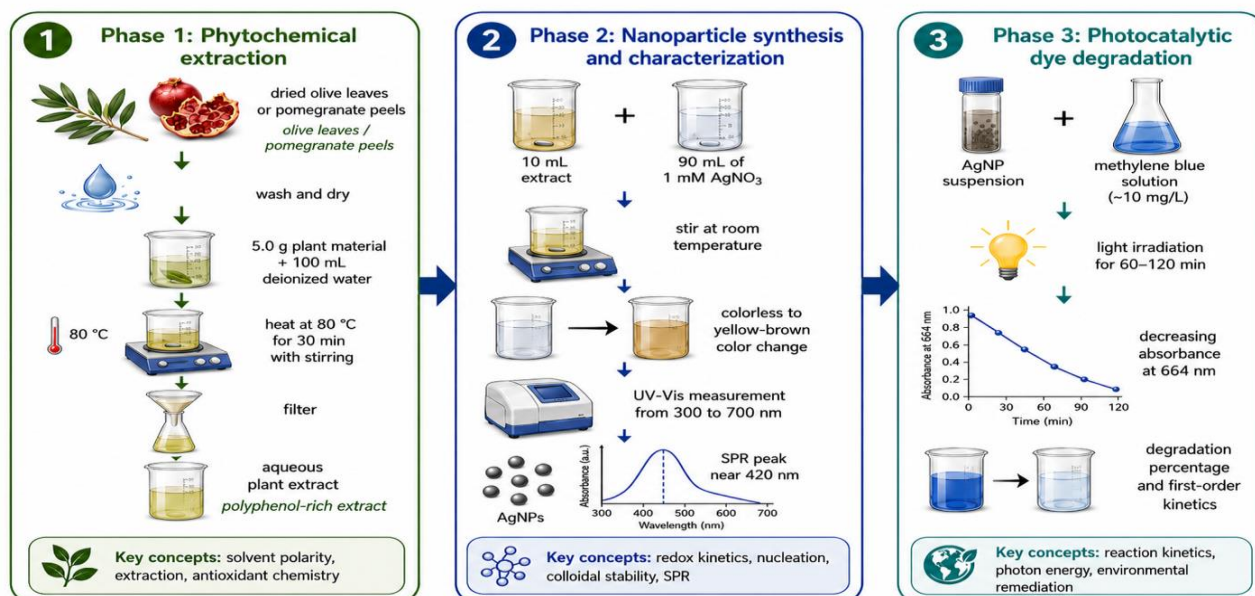


Figure 3, Three-phase laboratory workflow of the proposed green nanotechnology curriculum

4.1 Design Rationale and Scope

The framework is designed for integration into existing undergraduate physical chemistry laboratory sequences, typically in the second or third year of chemistry, materials science, or environmental engineering programs. It does not require full curriculum replacement. Rather,

it substitutes one or two conventional synthesis exercises with a three-phase biogenic synthesis sequence that can be completed over two or three laboratory sessions. This incremental model is consistent with previous successful efforts to embed green chemistry into existing undergraduate courses without wholesale redesign (Timmer et al., 2018; Zhang et al., 2023). The design is guided by three practical requirements. First, the protocol should avoid reagents that exceed moderate hazard classifications whenever possible. Second, the work should be feasible in a standard teaching laboratory, with UV-Vis spectrophotometry as the preferred but not absolutely essential characterization method. Third, waste generation should be minimized, segregated, and made visible to students as part of the learning process. These requirements reflect the broader argument that laboratory culture, not only individual experiments, must be reshaped if green chemistry is to become durable in undergraduate education (O'Neil et al., 2021; Grieger et al., 2022).

4.2 Phase One: Phytochemical Extraction

In the first phase, students prepare an aqueous extract from one of two locally available plant materials: dried olive leaves (*Olea europaea* L.) or dried pomegranate peel (*Punica granatum* L.). Both materials are compatible with the logic of green synthesis because they contain phytochemicals capable of participating in metal ion reduction and particle stabilization. Olive leaf extracts, for example, are rich in phenolic compounds such as oleuropein, while pomegranate peel is widely reported to contain ellagic acid and related polyphenolic constituents (Alotaibi et al., 2024; Bergal et al., 2022; Joshi et al., 2018).

A standard teaching protocol may involve washing and air-drying the plant material, adding 5.0 g to 100 mL of deionized water, heating the mixture to about 80°C with stirring for 30 minutes, cooling it to room temperature, and filtering it to remove solids. The extract is then used immediately or stored at 4°C for no more than 24 hours. The phase introduces polarity-guided extraction, aqueous solvent selection, hydrogen bonding, and the chemical role of plant phenolics. It also prepares students to ask a useful experimental question: if olive leaves and pomegranate peels differ in phytochemical composition, how might that difference influence nanoparticle formation?

Learning objectives - Phase One: By the end of this phase, students should be able to describe the role of plant polyphenols as reductants and capping agents; explain why aqueous extraction is preferable to organic solvent extraction on safety and sustainability grounds; and predict qualitatively how extract concentration or composition might influence subsequent nanoparticle synthesis.

4.3 Phase Two: Nanoparticle Synthesis and Characterization

In the second phase, students add a measured volume of plant extract, for example 10 mL, dropwise to 90 mL of 1 mM aqueous silver nitrate under constant stirring at room temperature. The reaction is monitored visually for a color change from colorless to yellow-brown, which often appears within 10-30 minutes depending on extract composition, pH, and concentration (Bergal et al., 2022; Vanlalveni et al., 2021).

Where UV-Vis spectroscopy is available, students record absorbance spectra at 10 minute intervals from 300 to 700 nm and track the emergence of the SPR band. The spectral data allow the instructor to connect visual observation to optical properties, plasmonics, colloidal chemistry, and structure-property relationships (Alotaibi et al., 2024; Nasrollahzadeh et al., 2019). Where such instrumentation is unavailable, a simple colorimetric comparison or a low-cost spectrophotometer attachment can be used as a functional teaching substitute, although with more limited analytical precision.

A central learning opportunity in this phase is inter-group variability. Different student groups may obtain different SPR peak positions, absorbance intensities, or colloid appearances despite using nominally similar procedures. Rather than treating this only as experimental failure, the instructor can frame it as evidence of uncontrolled variables and biological variability. This

approach is consistent with inquiry-based laboratory design because students must reason from imperfect evidence, identify likely causes of variation, and propose improvements to the protocol (Hmelo-Silver et al., 2007; Krajcik & Shin, 2014).

Learning objectives; Phase Two: Students should be able to relate the visible color change to SPR and nanoscale electron behavior; interpret a UV-Vis spectrum as evidence of nanoparticle formation; and identify controllable and less controllable variables that influence synthesis outcomes.

4.4 Phase Three: Environmental Application - Photocatalytic Dye Degradation

In the final phase, students apply the synthesized nanoparticle colloid to a model wastewater system prepared by dissolving methylene blue in deionized water, for example at approximately 10mg/L. A measured volume of nanoparticle suspension added to the dye solution, and the mixture is exposed to sunlight, a solar simulator, or a UV lamp for 60-120minutes. Degradation monitored by measuring absorbance at 664nm, the characteristic absorption maximum of methylene blue, at regular intervals (Joshi et al., 2018; Singh et al., 2018).

Students calculate degradation percentage from the ratio between initial and current absorbance values and then plot degradation curves. Where appropriate, they fit the data to a pseudo-first-order kinetic model, reinforcing prior instruction in reaction kinetics and giving students a quantitative basis for comparing photocatalytic performance. This phase provides a direct bridge between physical chemistry and environmental engineering because it links absorbance, rate laws, light-driven reactions, and pollutant removal (Makhalanyane et al., 2020; Shahzadi et al., 2025).

The environmental value of this phase is not merely illustrative. Dye contamination is a common model problem in photocatalysis research and provides students with a manageable way to examine broader questions of wastewater treatment, materials selection, and the environmental promise and limits of nanotechnology (Duan et al., 2015; Singh et al., 2018). By connecting plant-derived materials to water treatment, the framework supports sustainability competencies through practice rather than lecture alone (Rieckmann, 2018; UNESCO, 2017).

Learning objectives - Phase Three: Students should be able to calculate and interpret photocatalytic degradation percentages; fit kinetic data to a first-order model and extract a rate constant; and discuss the environmental relevance of photocatalytic water treatment, including how nanoparticle properties affect catalytic efficiency.

4.5 Concept Mapping Across the Framework

Table 1 summarizes the relationship between the three framework phases, core physical chemistry concepts, and the sustainability dimensions that can be emphasized during instruction. The purpose of the mapping is to help instructors integrate the framework into existing courses and design pre-laboratory and post-laboratory assessment activities.

Table 1. Concept mapping across the three-phase green nanotechnology framework.

Framework phase	Physical chemistry concepts	Sustainability / ESD dimension
Phase 1: Extraction	Solvent polarity; extraction equilibria; hydrogen bonding; antioxidant chemistry	Agricultural waste valorization; solvent choice as a green chemistry decision
Phase 2: Synthesis	Redox kinetics; nucleation and growth; colloidal stability; SPR; Beer-Lambert law	Waste minimization; ambient-condition processing; local biomass as a resource
Phase 3: Photocatalysis	Photon energy and electronic excitation; reaction kinetics; first-order rate laws; reactive oxygen species chemistry	Water treatment; dye pollution remediation; materials science for environmental benefit

5. Discussion

5.1 Principal Strengths of the Framework

The framework's most important strength is its integration of three dimensions that are often treated separately in higher education: scientific rigor, safety and sustainability, and local relevance. Plant-mediated synthesis using locally available materials is not merely a compromise for institutions with limited resources. It is a principled example of context-sensitive materials science and green chemistry education (Anastas & Warner, 1998; Kharissova et al., 2019). Students who complete the sequence do more than follow a recipe; they work through a small-scale version of applied research, moving from raw material selection to synthesis, characterization, and environmental testing.

A second strength is the transparency of the underlying chemistry. Unlike some demonstration-based nanotechnology activities, plant-mediated nanoparticle synthesis produces intermediate and final states that are both visible and conceptually interpretable. The color change that accompanies nanoparticle formation is not a superficial visual effect; it is connected to nanoscale electronic behavior and can be explored through SPR and UV-Vis spectroscopy (Nasrollahzadeh et al., 2019; Sweeney et al., 2006). This link between observation and theory is pedagogically powerful and helps students move from memorizing nanoscale concepts to reasoning with them.

A third strength is adaptability. In a physical chemistry course, the instructor may emphasize SPR, colloidal stability, and kinetic modeling. In an environmental chemistry course, the focus may shift toward photocatalysis, dye degradation, and water treatment. In a materials science course, the same sequence can be used to discuss synthesis-structure-property relationships. This adaptability makes the framework practical for institutions that cannot afford major curriculum restructuring but can introduce targeted laboratory reform (Timmer et al., 2018; Zhang et al., 2023).

5.2 Limitations and Challenges

The most important technical limitation is reproducibility. Plant extract composition varies with species, provenance, season, storage conditions, maturity, and extraction method. Two reactions prepared from the same nominal plant material may produce nanoparticles with different sizes, SPR peak positions, colloidal stability, or catalytic activity. This variability is well documented in the green synthesis literature and should not be minimized (Jadoun et al., 2021; Mustapha et al., 2022; Shahzadi et al., 2025).

Nevertheless, the educational setting allows this limitation to be handled productively. If students are prepared in advance to expect biological variability, they can treat divergent results as data to be explained rather than as failed work. This reframing requires careful instruction, but it also reflects authentic scientific reasoning. Students learn that experimental systems are not always idealized, and that scientific judgment often begins where procedural uniformity ends (Hmelo-Silver et al., 2007; Krajcik & Shin, 2014).

A second limitation is that the framework has not yet been empirically validated in Libyan university classrooms. Its claims about learning outcomes, student motivation, safety improvement, and waste reduction are grounded in broader green chemistry and sustainability education research, but they require local testing (Armstrong et al., 2018; Grieger et al., 2022; Leal Filho et al., 2018). This is not a minor gap; it is the central agenda for future work.

A third limitation concerns institutional culture. A single green laboratory activity cannot, by itself, create a sustainable laboratory system. Durable change also requires waste segregation, safety training, procurement policies that favor less hazardous alternatives, and departmental accountability. The proposed framework can provide a visible model of green practice, but its long-term effect depends on broader institutional commitment (O'Neil et al., 2021; UNESCO, 2017).

5.3 Pedagogical Implications

From a teaching perspective, the framework represents a form of authentic science education. Students prepare extracts, synthesize materials, observe unexpected variation, interpret data, and test an environmental application. This sequence is structurally closer to real inquiry than to traditional verification laboratories in which students simply confirm a known result (Blonder & Sakhini, 2015; Eilks & Hofstein, 2015).

The framework also supports sustainability learning at more than one level. At the cognitive level, students learn concepts such as reduction, SPR, colloidal stabilization, and photocatalytic kinetics. At the practical level, they work with safer solvents, milder conditions, and locally available biomass. At the ethical and professional level, they consider how scientific decisions affect waste, safety, and environmental outcomes. This layered learning design aligns with contemporary ESD competency frameworks, which emphasize integrated problem-solving and systems thinking (Brundiers et al., 2021; Rieckmann, 2018; Wiek et al., 2011).

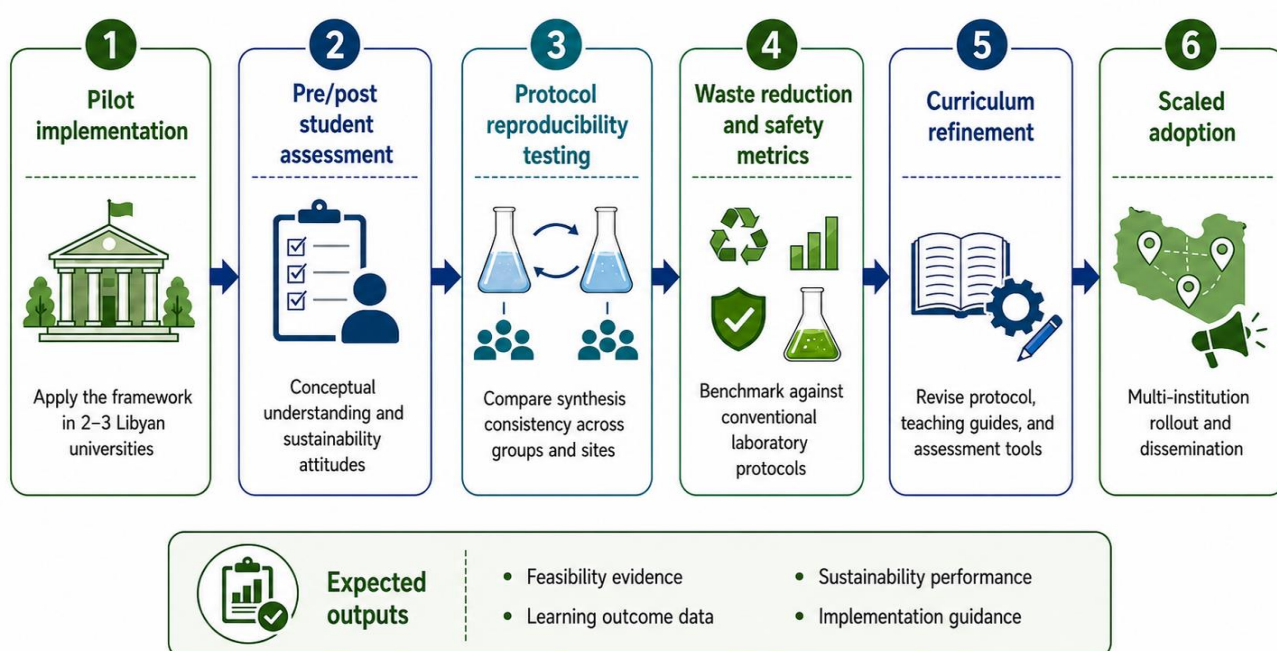


Figure 4. Proposed pilot validation pathway for the curriculum framework

6. Conclusion

This paper has proposed a structured curriculum framework for integrating green nanotechnology into undergraduate science and engineering programs in Libyan universities. The framework rests on three claims: that biogenic nanoparticle synthesis is chemically meaningful and practically accessible in resource-constrained teaching laboratories; that the observable phenomena it produces can support the teaching of core physical chemistry concepts; and that its connection to local plant materials and environmental challenges gives it a relevance that many generic laboratory exercises lack.

The paper advances three specific contributions. It provides an explicit concept-to-phase curriculum mapping that makes the educational logic of the framework visible and assessable. It reframes biological variability as a pedagogical resource rather than only a methodological problem. Finally, it presents a contextually grounded model that takes seriously the material, environmental, and institutional conditions of Libyan higher education.

At the same time, the framework should be regarded as a starting point rather than a completed intervention. The next step is a systematic pilot study implemented across two or three institutions. Such a study should collect pre- and post-intervention evidence on conceptual

understanding, sustainability attitudes, student engagement, reproducibility of synthesis outcomes, and waste reduction compared with conventional protocols. If future validation confirms feasibility and educational effectiveness, the framework could contribute not only to green chemistry education but also to a broader effort to build a scientifically rigorous, environmentally responsible, and locally relevant higher education system in Libya.

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