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PESQUISA EMPÍRICA

Material suplementar

Web-Based Interactive Multimedia as A Catalyst for Science Process Skills and Scientific Literacy in Inquiry-Based Learning

Multimídia Interativa Baseada na Web como Catalisadora das Habilidades de Processos Científicos e do Letramento Científico na Aprendizagem Baseada em Investigação

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Complete Scientific Literacy (SL) Test Items

This supplementary material contains the complete 10-item Scientific Literacy test used as both pretest and posttest in the study. Items are organized according to the three OECD (2023) PISA scientific literacy competency domains and contextualized within Green Chemistry inquiry themes. All items were dichotomously scored (2 = correct, 0 = incorrect).

Competency Domain 1: Explaining Phenomena Scientifically (Items 1–4)

Item 1: A chemistry student observes that baking soda ($NaHCO_3$) reacts with vinegar (acetic acid) to produce carbon dioxide gas, water, and sodium acetate. She notices that the reaction vessel becomes slightly cooler during the reaction. Using your knowledge of chemical bonding and energy transfer, explain why the temperature of the mixture decreases during this reaction.

Expected Response: Students should explain that in an endothermic reaction, the energy absorbed in breaking reactant bonds exceeds the energy released in forming product bonds, resulting in a net absorption of thermal energy from the surroundings—causing the observed temperature drop. Accept responses that correctly identify energy absorption from the surroundings and link it to bond-breaking/forming concepts.

OECD Competency: Explaining phenomena scientifically | GC Theme: Safer chemical reactions and waste reduction

Item 2: A company produces biodegradable packaging from corn starch instead of conventional petroleum-based plastic. A student claims: *"Corn starch packaging is more environmentally friendly because it is made from a renewable resource and can be broken down by microorganisms in soil."* Identify the two scientific principles from Green Chemistry that best support this claim, and explain the chemical basis for biodegradation.

Expected Response: Students should identify (1) the use of renewable feedstocks (GC Principle 7) and (2) design for degradation (GC Principle 10). Biodegradation occurs because microbial enzymes can cleave the ester/glycosidic bonds in polysaccharide chains of starch, yielding CO_2 and H_2O as end products.

OECD Competency: Explaining phenomena scientifically | GC Theme: Renewable feedstocks and biodegradable materials

Item 3: Liquid soap is commonly produced using a saponification reaction between vegetable oil (a triglyceride) and sodium hydroxide. Explain why saponification using plant-derived oils is considered a greener synthesis route compared to petroleum-derived surfactant production, and identify the chemical property of the product that makes it effective as a cleaning agent.

Expected Response: Plant-derived oils are renewable and typically biodegradable (GC Principles 7 and 10), whereas petroleum feedstocks are non-renewable. Saponification yields soap molecules with a polar (hydrophilic) carboxylate head and a non-polar (hydrophobic) hydrocarbon tail; this amphiphilic structure enables emulsification of oily dirt in water.

OECD Competency: Explaining phenomena scientifically | GC Theme: Safer synthesis routes and atom economy

Item 4: A textile factory discharges wastewater containing synthetic dye molecules into a nearby river. A scientist reports that the dye concentration drops significantly after sunlight exposure. Explain the photochemical process responsible for this observation, and assess whether photodegradation alone constitutes a sustainable wastewater treatment strategy according to Green Chemistry principles.

Expected Response: UV radiation from sunlight can break covalent bonds in dye molecules through photolysis or photocatalytic oxidation, generating smaller, less chromophoric fragments. However, photodegradation alone may not fully mineralize complex organic dyes to non-toxic CO_2 and H_2O; some intermediates may remain toxic. GC Principles 1 (waste prevention) and 4 (safer chemistry) require that treatment processes achieve complete detoxification, not merely concentration reduction.

OECD Competency: Explaining phenomena scientifically | GC Theme: Waste prevention and non-toxic chemical processes

Competency Domain 2: Evaluating and Designing Scientific Enquiry (Items 5–7)

Item 5: A student designs an experiment to compare the biodegradability of two types of plastic packaging: a conventional polyethylene bag and a bio-based polylactic acid (PLA) bag. Her experimental plan states: *"I will bury both bags in garden soil for 30 days and observe which one looks more degraded."* Identify two methodological weaknesses in this experimental design, and suggest specific improvements that would make the experiment more scientifically valid.

Expected Response: Weaknesses may include: (1) relying on visual appearance rather than quantitative mass loss measurement; (2) lack of controlled variables (e.g., soil type, temperature, moisture level, microbial population); (3) 30 days may be insufficient for measurable PLA degradation. Improvements should include: mass measurements before and after; controlled laboratory conditions; use of standardized soil with known microbial activity; multiple replicate bags; and longer duration or accelerated testing conditions.

OECD Competency: Evaluating and designing scientific enquiry | GC Theme: Biodegradable materials and experimental design validity

Item 6: A research team investigates whether replacing chlorinated solvents with ethanol as a reaction medium reduces the hazard profile of a chemical synthesis reaction. The team plans to measure product yield, solvent toxicity (LD_{50} values from the literature), and waste volume generated. Evaluate whether this experimental design adequately tests the Green Chemistry claim that *"safer solvents can maintain acceptable product yields while significantly reducing chemical hazards."* Identify one additional variable the team should measure and explain its relevance.

Expected Response: The design adequately addresses yield comparison and hazard profiling using LD_{50} as a toxicity surrogate. An additional variable could be atom economy (to assess how efficiently reactants are converted to desired product), energy consumption per unit of product (GC Principle 6), or solvent recyclability. Students should justify why their chosen variable is relevant to the GC framework.

OECD Competency: Evaluating and designing scientific enquiry | GC Theme: Safer solvents and reagents

Item 7: A student reads the following claim in an online article: *"All natural cleaning products are automatically safer and more environmentally friendly than synthetic chemical cleaners."* Design a scientific investigation that could test this claim. Your answer should identify the independent and dependent variables, describe a measurement procedure, and explain what result would confirm or refute the claim.

Expected Response: Independent variable: type of cleaning product (natural vs. synthetic). Dependent variables: aquatic toxicity (e.g., using Daphnia bioassay), biodegradation rate, cleaning efficacy (measured by standardized soil removal tests). Procedure should include controlled testing conditions and replicated trials. A result refuting the claim would show that some natural ingredients (e.g., citrus-derived limonene at high concentrations) display significant ecotoxicity, or that some synthetic products biodegrade rapidly and show low toxicity.

OECD Competency: Evaluating and designing scientific enquiry | GC Theme: Non-toxic formulations and real-world chemical safety

Competency Domain 3: Interpreting Data and Evidence Scientifically (Items 8–10)

Item 8: The table below presents atom economy values and hazard classification scores for three alternative synthesis routes (A, B, and C) for producing a common pharmaceutical compound:

Route A: Atom economy = 85%; Hazard score = 2 (low hazard); Waste generated = 8 g per 100 g product

Route B: Atom economy = 62%; Hazard score = 4 (moderate hazard); Waste generated = 22 g per 100 g product

Route C: Atom economy = 91%; Hazard score = 7 (high hazard); Waste generated = 5 g per 100 g product

Based on these data, which synthesis route best aligns with Green Chemistry principles? Justify your answer using evidence from at least two GC criteria, and explain why Route C is not automatically the best choice despite its highest atom economy.

Expected Response: Route A best aligns with GC principles because it combines high atom economy (85%) with low hazard (score = 2) and acceptable waste generation (GC Principles 1, 3, and 4). Route C, despite the highest atom economy (91%), carries a high hazard score (7), violating GC Principle 4 (design for safer chemistry). Students must demonstrate multi-criteria reasoning: atom economy alone is insufficient; hazard, waste, and safety must be weighed simultaneously.

OECD Competency: Interpreting data and evidence scientifically | GC Theme: Atom economy and safer chemical design

Item 9: [This item corresponds to the sample item presented in the main text of the manuscript.] A factory produces cleaning products using two alternative synthesis pathways. Pathway A generates 15% waste by mass while using a non-toxic solvent, whereas Pathway B generates 5% waste but requires a chlorinated solvent classified as hazardous. Based on Green Chemistry principles, which pathway is more sustainable, and what evidence supports your decision?

Expected Response: Pathway A is more sustainable. Although Pathway B generates less waste by mass (GC Principle 1), it relies on a chlorinated solvent classified as hazardous, which conflicts with GC Principles 4 (safer chemistry) and 5 (safer solvents and auxiliaries). Pathway A's use of a non-toxic solvent preserves both human health and environmental safety criteria, which take priority over waste reduction when hazardous substances are involved. Students should demonstrate that GC decision-making requires integrating multiple principles rather than optimizing a single variable.

OECD Competency: Interpreting data and evidence scientifically | GC Theme: Waste reduction and safer solvents

Item 10: A student measures the pH of wastewater samples collected upstream (pH = 7.1) and downstream (pH = 4.3) of a textile factory. She also collects data showing that fish

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biodiversity drops from 12 species upstream to 3 species downstream. Interpret these data: (a) explain the likely chemical cause of the pH change; (b) propose one Green Chemistry-based intervention the factory could implement to prevent this problem; and (c) identify one limitation of using fish biodiversity as the sole indicator of wastewater impact.

Expected Response: (a) The pH decrease from 7.1 to 4.3 suggests acidic effluent discharge, likely from dye-fixing agents, acid-catalyzed reactions, or metal salt effluents used in textile processing. (b) GC interventions could include: implementing closed-loop water recycling (Principle 1 — waste prevention), switching to non-toxic, pH-neutral dyeing auxiliaries (Principle 4 — safer chemistry), or pre-treating acidic effluent with base neutralization before discharge. (c) Fish biodiversity is an indirect ecological indicator that reflects cumulative ecosystem damage but cannot isolate specific chemical causes; it also lags behind chemical changes and may be affected by confounding factors such as habitat destruction or temperature changes.

OECD Competency: Interpreting data and evidence scientifically | GC Theme: Environmental impact assessment and waste prevention

Note. All items were dichotomously scored: 2 = correct/complete response demonstrating the identified scientific reasoning; 0 = incorrect or absent response. Partial credit was not applied. Scoring keys were reviewed and confirmed by the six expert validators during instrument validation.