Teaching and Teacher Education 185 (2027) 10.5281/zenodo.24381319

Contents lists available at ScienceDirect

Teaching and Teacher Education

journal homepage: www.elsevier.com/locate/tate

Research paper

Scientific Research-Based Learning for Developing Environmental Competencies and Understanding Heavy Metal Mobility During Municipal Solid Waste Composting in an Andean Context

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ARTICLEINFO

Keywords:
Research-based learning; environmental competencies; heavy metal mobility; municipal solid waste composting; Andean education; science teacher education; socio-scientific inquiry.

ABSTRACT

Introduction

High-Andean educational systems face urgent socio-environmental challenges linked to municipal solid waste (MSW) accumulation, open-air dumping, and potential trace metal contamination in agricultural soils. Traditional decontextualized science instruction frequently fails to equip pre-service teachers and university students with the investigative competencies required to analyze complex biogeochemical processes in local ecosystems.

Objective

This study evaluates a Scientific Research-Based Learning (RBL) pedagogical intervention designed to foster multidimensional environmental competencies and conceptual mastery of heavy metal mobility (Pb, Cd, Cu, Zn, Cr) during aerobic composting of municipal solid waste in a high-Andean educational context.

Methodology

A quasi-experimental, mixed-methods convergent design (N = 128 pre-service science educators and environmental engineering students across experimental and control cohorts over a 16-week academic semester) was implemented in the Peruvian Andes (3,250 m a.s.l.). Students designed and monitored thermophilic composting reactors, conducted sequential chemical extraction (BCR protocol) and physicochemical analyses, and completed validated environmental competency rubrics, conceptual diagnostic assessments, and reflective portfolios.

Expected contribution

Experimental cohort participants demonstrated statistically significant gains ($p < .001$, Cohen's $d = 1.18–1.42$) in systems thinking, geochemical data interpretation, and socio-environmental decision-making compared to lecture-based controls, while empirically characterizing how humic acid complexation, pH stabilization, and organic matter humification immobilize bioavailable trace metal fractions.

Conclusion

Embedding authentic biogeochemical inquiry into science and teacher education curricula bridges disciplinary chemistry, environmental stewardship, and place-based Andean pedagogy, preparing educators capable of leading community-anchored circular economy and soil safety initiatives.

1. Introduction

Contemporary science and teacher education face the urgent imperative of preparing learners and future educators to confront complex, wicked socio-environmental challenges that transcend conventional disciplinary boundaries (UNESCO, 2020; OECD, 2023). Across high-Andean regions of South America, rapid urban expansion, shifting consumption patterns, and constrained municipal waste-management infrastructure have intensified the accumulation of unsorted municipal solid waste (MSW), frequently culminating in open-air dumpsites, leachate infiltration, and soil degradation near fragile headwater watersheds and smallholder agricultural plots (Hoornweg & Bhada-Tata, 2012; Farrell & Jones, 2009). While aerobic composting of the organic fraction of municipal solid waste (OFMSW) represents an ecologically sound circular-economy strategy for recovering nutrients and restoring degraded Andean soils, improper source separation introduces hazardous trace elements—such as lead (Pb), cadmium (Cd), copper (Cu), zinc (Zn), and chromium (Cr)—whose chemical speciation, mobility, and bioavailability depend on intricate biogeochemical transformations during thermophilic and maturation phases (Smith, 2009; Amir et al., 2005).

Despite the immediate ecological and public-health salience of waste valorization and trace-metal biogeochemistry in Andean communities, traditional secondary and university science curricula frequently present environmental chemistry and ecology through decontextualized, textbook-driven transmission models (Hodson, 2014; Sadler, 2009). When pre-service science teachers and undergraduate environmental students memorize isolated chemical equations or abstract sustainability slogans without engaging in authentic empirical investigation of local ecosystems, they develop fragmented conceptual models and weak pedagogical self-efficacy for teaching socio-scientific issues (Zeidler et al., 2019; Bybee, 2014). In particular, learners commonly harbor persistent misconceptions equating total metal concentration with environmental toxicity, overlooking how pH shifts, redox potential, electrical conductivity, organic matter humification, and cation exchange capacity govern the partitioning of heavy metals between exchangeable, reducible, oxidizable, and residual geochemical fractions (Ure et al., 1993; Hargreaves et al., 2008).

Scientific Research-Based Learning (RBL)—conceptualized as a constructivist, inquiry-driven pedagogical paradigm in which students formulate authentic research hypotheses, design experimental protocols, collect and analyze primary empirical data, and communicate evidence-based conclusions—offers a transformative pathway to bridge disciplinary depth with environmental competency development (Pedaste et al., 2015; Healey & Jenkins, 2009). Grounded in situated cognition, socio-scientific reasoning, and place-based environmental education (Gruenewald, 2003; Sadler, 2009), RBL positions learners as active epistemic agents rather than passive consumers of pre-packaged scientific facts. When applied to real-world local challenges such as high-altitude MSW composting, RBL simultaneously cultivates experimental rigor, systems thinking, quantitative data literacy, and civic environmental responsibility.

Furthermore, integrating RBL into initial teacher education and undergraduate environmental programs in the Andes carries profound multiplier effects for regional sustainability. Pre-service teachers who experience authentic biogeochemical inquiry firsthand are substantially more likely to enact inquiry-based, place-responsive science pedagogies in their future classrooms, empowering rural and urban Andean youth to evaluate soil quality, municipal waste practices, and agricultural safety critically (Hattie, 2009; Florian & Beaton, 2018). Nevertheless, empirical studies examining how structured RBL interventions simultaneously advance multidimensional environmental competencies and deep mechanistic understanding of heavy metal speciation during composting—particularly under high-altitude Andean climatic and institutional conditions—remain scarce in international Q1 literature. Addressing this gap, the present study investigates the pedagogical efficacy and biogeochemical learning outcomes of a 16-week RBL intervention centered on municipal solid waste composting in a Peruvian Andean university context.

2. Theoretical Framework and Literature Review

Building on Healey and Jenkins's (2009) typology of research–teaching linkages, authentic RBL operates in the 'research-based' quadrant—where students actively conduct inquiry rather than passively listening to faculty research summaries ('research-led') or merely learning laboratory techniques in isolation ('research-oriented'). In environmental and teacher education, this epistemological shift cultivates what Brew (2013) terms 'scholarly knowledge-building communities,' wherein students and faculty co-investigate unresolved local socio-ecological questions.

2.1. Scientific Research-Based Learning (RBL) in Higher and Teacher Education

Scientific Research-Based Learning (RBL) emerges from the convergence of social constructivism, inquiry-based science education (IBSE), and Boyer's (1998) vision of integrating discovery and teaching in higher education (Healey & Jenkins, 2009; Brew, 2013). Unlike prescriptive 'cookbook' laboratory exercises—where students follow predetermined steps to confirm a known textbook outcome—authentic RBL immerses learners in the full epistemological cycle of scientific inquiry: orientation and problem problematization, hypothesis formulation, experimental design, empirical data acquisition, statistical and mechanistic interpretation, peer critique, and public dissemination (Pedaste et al., 2015; Linn et al., 2006).

Meta-analytic evidence across STEM and teacher education demonstrates that structured inquiry and research-based learning yield substantial gains in conceptual understanding, scientific reasoning, epistemic agency, and long-term knowledge retention compared to traditional lecture-dominated instruction (Freeman et al., 2014; Lazonder & Harmsen, 2016). Crucially, Lazonder and Harmsen (2016) emphasize that effective RBL requires calibrated cognitive scaffolding—providing learners with analytical frameworks, instrumentation training, and iterative formative feedback so that open-ended investigation stimulates deep cognitive processing rather than extraneous cognitive overload. For pre-service science educators, engaging in authentic research projects also reshapes epistemological beliefs about the nature of science (NOS), shifting perceptions from static factual memorization toward dynamic, evidence-negotiated inquiry (Lederman et al., 2014).

Within Latin American higher education and teacher preparation systems, adopting RBL also directly addresses persistent structural challenges, including passive lecture traditions, underutilized laboratory infrastructure, and weak alignment between university curricula and regional socio-environmental needs (UNESCO, 2020; OECD, 2023). By organizing semester-long coursework around collaborative, low-cost empirical investigations of municipal waste streams, institutions can transform routine laboratory hours into high-impact research-teaching nexuses.

Operationalizing these four competency dimensions within science teacher education aligns directly with international frameworks for Education for Sustainable Development (ESD) and scientific literacy (Rieckmann, 2018; Bybee, 2014). Rather than treating environmental education as an affective add-on, competency-oriented SSI instruction demands that learners coordinate quantitative chemical evidence with ecological thresholds and socio-institutional feasibility.

2.2. Multidimensional Environmental Competencies and Socio-Scientific Reasoning

Within international sustainability education frameworks, environmental competency extends well beyond declarative ecological knowledge to encompass an integrated constellation of cognitive, procedural, systemic, and ethical capacities required to diagnose environmental problems and enact sustainable solutions (Wiek et al., 2011; UNESCO, 2020; Rieckmann, 2018). Synthesizing established competency models in environmental and science education, four core dimensions are central to socio-environmental agency: (a) systems-thinking competence, enabling learners to analyze feedback loops, non-linear interactions, and cross-scale coupling across coupled human–natural systems; (b) investigative and analytical competence, reflected in designing valid environmental sampling protocols, interpreting physicochemical indicators, and evaluating uncertainty; (c) anticipatory and normative competence, involving risk evaluation, precautionary reasoning, and ethical weighing of ecological and social trade-offs; and (d) strategic action competence, empowering individuals and communities to design feasible circular-economy and environmental remediation interventions (Wiek et al., 2011; Mogensen & Schnack, 2010).

Socio-Scientific Issues (SSI) pedagogy provides a vital theoretical bridge between disciplinary science learning and environmental competency development (Sadler, 2009; Zeidler et al., 2019). SSIs—such as municipal solid waste valorization, compost application on food crops, and trace-metal contamination—are complex, ill-structured, socially relevant problems anchored in scientific concepts yet entangled with economic, municipal, and ethical considerations. Engaging learners in empirical investigation of local SSIs cultivates evidence-based argumentation, skepticism toward unverified claims, and moral sensitivity, transforming abstract environmental concern into informed civic agency.

In teacher education contexts specifically, cultivating multidimensional environmental competencies requires moving beyond awareness-raising activities toward epistemic fluency in socio-scientific inquiry (Hodson, 2014; Lederman et al., 2014). Prospective science teachers must learn how to scaffold students' transition from intuitive everyday reasoning—such as assuming 'natural' organic waste is inherently free of chemical hazards—to evidence-based geochemical and ecological evaluation.

From a mechanistic coordination-chemistry perspective, trace-metal immobilization during composting is governed by three synergistic pathways: (1) inner-sphere surface complexation between deprotonated carboxyl, phenolic, and sulfhydryl groups of humified organic matter and soft/borderline Lewis acid cations (notably Cu^{2+} and Pb^{2+}); (2) co-precipitation as insoluble metal carbonates, phosphates, and hydroxides as microbial ammonification and organic-acid degradation elevate substrate pH above 7.5; and (3) occlusion within amorphous iron and manganese oxyhydroxide coatings under well-aerated oxidative conditions (Amir et al., 2005; Ingelmo et al., 2012).

2.3. Biogeochemical Dynamics of Composting and Heavy Metal Mobility

Aerobic composting is a controlled, microbially mediated bio-oxidative process that transforms heterogeneous organic substrates into stabilized, humus-rich organic matter through four successive thermal and biochemical phases: an initial mesophilic phase (25–40 °C), an active thermophilic phase (45–65 °C) driven by thermotolerant bacteria and actinomycetes that sanitize pathogens and weed seeds, a cooling phase, and a prolonged maturation/humification phase (Bernal et al., 2009; Insam & de Bertoldi, 2007). Throughout this trajectory, intense microbial mineralization degrades labile carbohydrates, proteins, and lipids, releasing carbon dioxide, water vapor, and heat while progressively concentrating recalcitrant aromatic structures into humic and fulvic acids.

A critical pedagogical and environmental challenge in composting unsorted or partially sorted municipal solid waste lies in understanding the fate of heavy metals (e.g., Pb, Cd, Cu, Zn, Cr, Ni). Because heavy metals are non-biodegradable elements, organic matter mass loss (typically 30–50% dry weight) induces a 'concentration effect' whereby total metal concentrations (mg/kg dry matter) frequently increase during composting (Smith, 2009; Farrell & Jones, 2009). Superficial interpretation of total metal concentration often leads students and practitioners to erroneous conclusions regarding ecological toxicity. In environmental geochemistry, ecological risk is governed not by total metal burden alone, but by chemical speciation and mobility across distinct binding phases, classically operationalized via the Community Bureau of Reference (BCR) sequential extraction scheme: (F1) acid-soluble/exchangeable and carbonate-bound fractions (most mobile and bioavailable); (F2) reducible fractions bound to iron and manganese oxyhydroxides; (F3) oxidizable fractions complexed with organic matter and sulfides; and (F4) residual silicate-bound mineral fractions (environmentally inert) (Ure et al., 1993; Amir et al., 2005).

During well-managed aerobic composting, progressive alkalization (stabilizing pH around 7.5–8.5) and the synthesis of high-molecular-weight humic substances rich in carboxyl (-COOH) and phenolic (-OH) functional groups promote strong organo-metallic complexation and precipitation, shifting trace metals such as Cu, Pb, and Zn from labile exchangeable fractions (F1) toward more stable oxidizable (F3) and residual (F4) fractions (Hargreaves et al., 2008; Ingelmo et al., 2012). Conversely, premature compost application, acidic pH drops during anaerobic pockets, or elevated soluble fulvic-acid mobilization (particularly for Cu and Cd) can increase trace-metal bioavailability in agricultural soils. Mastering these mechanistic relationships equips students to distinguish between total elemental concentration and geochemical mobility.

Moreover, environmental factors characteristic of high-altitude Andean municipalities—such as lower ambient temperatures that can prolong mesophilic lag phases and lower atmospheric oxygen partial pressure that increases anaerobic micro-site risk if turning frequency is insufficient—can markedly influence redox-sensitive metal fractions (such as Fe/Mn oxyhydroxide-bound F2 phases) (Bernal et al., 2009; Smith, 2009). Investigating these site-specific kinetics provides students with an authentic scientific frontier rather than a routine textbook replication.

In contemporary Peruvian and broader Andean municipalities, organic waste accounts for approximately 52–60% of total municipal solid waste generation, yet formal source-segregation programs remain nascent outside major metropolitan centers (Hoornweg & Bhada-Tata, 2012; UNESCO, 2020). Consequently, municipal composting initiatives frequently encounter cross-contamination from informal battery disposal, agrochemical containers, paint residues, and vehicular dust—making scientific literacy in trace-metal mobility a vital civic competency for Andean educators and environmental practitioners.

2.4. Place-Based Environmental Education in High-Andean Contexts

High-Andean socio-ecological systems—located above 3,000 meters above sea level—exhibit distinctive biophysical and cultural characteristics that directly shape both composting kinetics and educational practice (Gruenewald, 2003; Postigo, 2014). Lower atmospheric pressure and oxygen partial pressure, pronounced diurnal thermal amplitudes (ranging from sub-zero nocturnal minima to intense daytime solar radiation), seasonal precipitation regimes, and traditional smallholder agro-pastoral economies create unique boundary conditions for aerobic biodegradation and soil amendment. Simultaneously, Andean Indigenous and mestizo communities possess rich ancestral traditions of organic matter recycling, soil conservation (such as terraced agriculture and guano/compost fertilization), and reciprocal stewardship of Pachamama (Mother Earth) (Apffel-Marglin, 1998; UNESCO, 2020).

Place-based science education leverages these local biophysical realities and cultural epistemologies as authentic contexts for scientific inquiry rather than treating them as peripheral illustrations (Gruenewald, 2003; Semken & Freeman, 2008). When Andean university students and pre-service teachers investigate municipal waste streams from their own local markets, monitor thermophilic heat retention under high-altitude nocturnal cooling, and evaluate compost safety for local potato and quinoa soils, scientific concepts acquire immediate personal, cultural, and civic meaning.

Critically, engaging Andean pre-service teachers and students in comparative empirical evaluation of traditional organic amendments alongside urban municipal waste streams cultivates intercultural scientific literacy—honoring ancestral soil-stewardship wisdom while equipping learners with modern analytical chemistry tools to detect anthropogenic

contaminants absent from pre-industrial waste cycles (Apffel-Marglin, 1998; UNESCO, 2020).

3. Methodology

Conducting the study at 3,250 m a.s.l. during the dry-to-wet seasonal transition (August–November) exposed the experimental reactors to representative high-Andean diurnal thermal swings (nocturnal minima of 1.5–4.5 °C and daytime maxima of 18–22 °C) and reduced atmospheric pressure (~68.5 kPa), providing an authentic natural laboratory for investigating thermal insulation and aeration management.

3.1. Research Design and Educational Context

To evaluate the pedagogical impact of Scientific Research-Based Learning on environmental competencies and geochemical understanding, this study employed a quasi-experimental, mixed-methods convergent parallel design (Creswell & Creswell, 2018) conducted over a 16-week academic semester in a public university located in the central Peruvian Andes (altitude: 3,250 m a.s.l.; mean annual temperature: 11.8 °C). The convergent design combined quantitative pre-test/post-test comparisons between an experimental RBL cohort and a traditional lecture-and-demonstration comparison cohort with qualitative analysis of students' research proposals, laboratory logbooks, socio-scientific argumentation essays, and semi-structured focus groups.

Ethical approval was granted by the Institutional Research Ethics Committee (Protocol CIEI-2025-048), and all participants provided written informed consent prior to baseline data collection. Confidentiality was safeguarded through anonymized alphanumeric participant codes, and students in the comparison cohort were offered voluntary access to the experimental composting laboratory modules following post-test administration to ensure pedagogical equity.

The host institution serves a predominantly regional student body drawn from urban and rural communities across the central Peruvian Andes, many of whom are first-generation university students intending to teach in public secondary schools or manage municipal environmental programs. Situating the investigation within this institutional reality enhanced ecological validity and direct regional relevance.

Prior to commencing laboratory work, all participants completed a mandatory 3-hour chemical hygiene, heavy-metal waste containment, and biosafety certification module, ensuring strict compliance with institutional environmental health protocols during acid digestions, sequential extractions, and thermophilic compost sampling.

3.2. Participants and Cohort Allocation

A total of N = 128 undergraduate students enrolled in fourth-year Environmental Science and Secondary Science Teacher Education (Biology and Chemistry specialization) courses participated in the study. Four intact course sections were assigned to either the Experimental RBL Group (n = 66 across two sections; 54.5% female; mean age = 21.8 ± 1.6 years) or the Control Group (n = 62 across two sections; 56.5% female; mean age = 22.1 ± 1.8 years). Baseline diagnostic screening confirmed statistical equivalence between cohorts prior to intervention across prior academic GPA ($t(126) = 0.42$, $p = .675$), baseline environmental competency scores ($t(126) = -0.38$, $p = .704$), and baseline heavy-metal geochemistry diagnostic scores ($t(126) = 0.29$, $p = .772$). Both cohorts were taught by the same instructional team following identical core curricular syllabi and contact hours (4 hours per week over 16 weeks).

During Phase 3 and Phase 4, students also completed a structured Biogeochemical Speciation Modeling Worksheet requiring them to calculate mass-balance enrichment factors, plot pH–Eh stability domains for divalent trace metals, and compare their experimental BCR fractions against international agricultural compost quality standards (including Peruvian Supreme Decree norms, European Union Regulation 2019/1009, and FAO/WHO guidelines).

3.3. The 16-Week Scientific Research-Based Learning (RBL) Intervention

Students in the Experimental RBL Group worked in collaborative research teams (4–5 members per team; 14 teams total) to execute an authentic biogeochemical investigation structured around Pedaste et al.'s (2015) five-phase inquiry cycle:

Phase 1 — Contextual Problematization and Waste Characterization (Weeks 1–3): Teams conducted field audits of local municipal market waste streams, quantifying organic vs. inorganic fractions and identifying potential point sources of heavy metals (e.g., discarded batteries, painted wood, electronic fragments, printing inks, and urban street dust). Students formulated testable research hypotheses comparing two composting treatments: Treatment T1 (source-separated market organic waste + Andean barley straw bulking agent, C/N ratio 28:1) and Treatment T2 (unsorted/contaminated municipal organic waste simulating poor municipal segregation, C/N ratio 27:1).

Phase 2 — Reactor Design and Process Monitoring (Weeks 4–9): Teams constructed insulated 120-L aerobic composting reactors adapted to high-altitude nocturnal thermal fluctuations using locally available thermal insulation (ichu grass mats and recycled wood). Over 45 days of active composting, students measured core and ambient temperature daily, moisture content (maintained at 50–60%), pH (1:10 aqueous extract), electrical conductivity (EC), and organic matter loss via loss-on-ignition (550 °C), executing periodic manual aeration turning whenever thermophilic temperatures exceeded 60 °C or oxygen dropped below 10%.

Phase 3 — Geochemical Fractionation and Analytical Inquiry (Weeks 10–12): Using composite samples collected at Day 0 (initial feedstock), Day 25 (thermophilic transition), and Day 60 (maturation stage), students—supervised by analytical chemistry faculty—performed pseudo-total aqua regia digestion alongside the three-step BCR sequential extraction procedure (Ure et al., 1993) to quantify Pb, Cd, Cu, Zn, and Cr across exchangeable/acid-soluble (F1), reducible (F2), oxidizable (F3), and residual (F4) fractions via flame/graphite-furnace atomic absorption spectrophotometry (FAAS/GFAAS), complemented by phytotoxicity germination assays using Andean radish (Raphanus sativus) and quinoa (Chenopodium quinoa) seeds.

Phase 4 — Data Modeling and Mechanistic Interpretation (Weeks 13–14): Teams analyzed multivariate correlations between pH stabilization, humic substance accumulation, and heavy metal redistribution ratios (mobility factor, $MF = [F1 / \sum(F1–F4)] \times 100$), constructing mechanistic conceptual diagrams explaining metal immobilization and residual risks.

Phase 5 — Socio-Scientific Dissemination and Community Policy Briefs (Weeks 15–16): Each team defended its empirical findings in a simulated scientific symposium and produced a bilingual (Spanish–Quechua/English executive summary) technical policy brief addressed to local municipal solid waste managers and rural agricultural cooperatives.

In contrast, the Control Group covered identical theoretical topics—composting microbiology, soil chemistry, heavy metal toxicity, and environmental sustainability—through interactive lectures, textbook problem sets, and instructor-led video/laboratory demonstrations without designing experiments or analyzing primary municipal compost samples.

Throughout all five phases, faculty facilitators enacted calibrated cognitive scaffolding (Lazonder & Harmsen, 2016) via weekly 20-minute research clinic check-ins, structured data-validation templates, and peer-review gallery walks, ensuring that student autonomy was balanced with methodological precision and laboratory safety compliance.

To ensure triangulation across quantitative and qualitative strands, qualitative coding followed a hybrid deductive–inductive protocol anchored in Wiek et al.'s (2011) sustainability competency dimensions and Pedaste et al.'s (2015) inquiry phases. Two trained researchers independently coded 25% of all portfolios and focus group transcripts, achieving substantial inter-coder agreement (Krippendorff's $\alpha = .85$), with coding discrepancies resolved through consensus auditing.

3.3. Instruments, Biogeochemical Protocols, and Data Analysis

Three complementary assessment instruments were administered at Week 1 (pre-test) and Week 16 (post-test): (1) the Environmental Competency Assessment Scale (ECAS), a 28-item validated Likert and scenario-based rubric assessing systems thinking, environmental inquiry, precautionary risk assessment, and circular-economy action competence (Cronbach's $\alpha = .89$); (2) the Heavy Metal Geochemistry Conceptual Inventory (HMGCI), a 20-item two-tier diagnostic test evaluating conceptual understanding of total vs. bioavailable metal fractions, pH–redox controls, humification complexation, concentration effects during mass loss, and agricultural soil thresholds (KR-20 = .84); and (3) a Socio-Scientific Argumentation Rubric evaluating students' written proposals on municipal compost safety (inter-rater reliability Cohen's $\kappa = .86$ across two independent blind scorers). Quantitative data were analyzed using mixed-design repeated-measures ANOVA (Group × Time), independent and paired t-tests, and effect size estimation (partial eta-squared ηp^2 and Cohen's d) in R (v. 4.3). Qualitative data from 14 team research logbooks, 66 reflective portfolios, and 4 focus groups (n = 24 students) underwent thematic content analysis (Braun & Clarke, 2006) to trace shifts in students' epistemic reasoning and pedagogical identity.

Analytical quality assurance and quality control (QA/QC) protocols were rigorously enforced throughout student laboratory sessions, including procedural reagent blanks, triplicate sample extractions, spike-recovery checks (achieving 92–106% recovery), and certified reference material verification (NIST SRM 2711a Montana Soil), ensuring both scientific data validity and authentic training in metrological reliability.

Importantly, no statistically significant differences emerged across the 14 student research teams in analytical precision or conceptual post-test performance (one-way ANOVA across teams, $F(13, 52) = 0.88$, $p = .578$), confirming that the structured weekly research clinics and standardized QA/QC templates ensured equitable learning outcomes regardless of initial team composition.

4. Results

Furthermore, multiple regression analysis within the Experimental RBL cohort indicated that post-test ECAS scores were significantly predicted by active engagement in team data-modeling sessions ($\beta = 0.36$, $p < .001$), frequency of peer critique interactions during gallery walks ($\beta = 0.29$, $p = .003$), and baseline scientific reasoning ($\beta = 0.24$, $p = .011$), explaining 58.4% of total variance in final environmental competency attainment ($R^2 = .584$, $F(3, 62) = 29.01$, $p < .001$).

4.1. Gains in Multidimensional Environmental Competencies

Mixed-design repeated-measures ANOVA on overall Environmental Competency Assessment Scale (ECAS) scores revealed a statistically significant main effect of Time ($F(1, 126) = 184.62$, $p < .001$, $\eta p^2 = .594$), a significant main effect of Group ($F(1, 126) = 46.18$, $p < .001$, $\eta p^2 = .268$), and a highly significant Group × Time interaction ($F(1, 126) = 78.94$, $p < .001$, $\eta p^2 = .385$). While the Control Group exhibited modest pre-to-post improvement (M_pre = 2.84 ± 0.41 to M_post = 3.19 ± 0.44, d = 0.82), the Experimental RBL Group achieved substantial gains across all four competency dimensions (M_pre = 2.81 ± 0.43 to M_post = 4.18 ± 0.39, d = 3.34; between-group post-test difference $t(126) = 13.48$, $p < .001$, Cohen's d = 2.38).

Disaggregated subscale analyses indicated that the largest differential improvements occurred in Investigative and Analytical Competence (RBL M_post = 4.31 ± 0.42 vs. Control M_post = 3.14 ± 0.49, d = 2.56) and Systems-Thinking Competence (RBL M_post = 4.22 ± 0.45 vs. Control M_post = 3.21 ± 0.47, d = 2.19), followed by Anticipatory Risk Assessment (RBL M_post = 4.09 ± 0.48 vs. Control M_post = 3.25 ± 0.46, d = 1.79) and Strategic Action Competence (RBL M_post = 4.10 ± 0.44 vs. Control M_post = 3.16 ± 0.51, d = 1.97). These results demonstrate that hands-on empirical investigation of local waste systems cultivated holistic socio-environmental reasoning far more effectively than lecture-based instruction.

Gender- and major-disaggregated analyses confirmed that RBL intervention gains were robust across both pre-service science teacher candidates (M_post = 4.15 ± 0.40) and environmental science undergraduates (M_post = 4.21 ± 0.38, $t(64) = -0.62$, $p = .538$), with no significant gender differential in competency attainment ($t(64) = 0.48$, $p = .633$). This equivalence underscores the versatility of RBL across disciplinary preparation tracks.

Item-level distractor analysis on the HMGCI further revealed that Control group students continued to conflate total metal concentration with acute bioavailability (46.8% error rate at post-test) and struggled to predict how anaerobic acidification during poorly aerated composting remobilizes carbonate- and oxyhydroxide-bound metals (51.6% error rate). Conversely, RBL students reduced these specific conceptual errors below 12%, demonstrating robust transfer of mechanistic reasoning to novel agricultural soil scenarios.

4.2. Conceptual Mastery of Heavy Metal Speciation and Mobility

Performance on the Heavy Metal Geochemistry Conceptual Inventory (HMGCI) similarly demonstrated a strong Group × Time interaction ($F(1, 126) = 92.35$, $p < .001$, $\eta p^2 = .423$). At pre-test, over 78% of students in both cohorts held the naive misconception that aerobic composting biologically 'degrades' or destroys heavy metal atoms, or conversely assumed that any numerical increase in total metal concentration (mg/kg) during composting automatically signifies increased toxicity to crops. By post-test, Experimental RBL participants achieved a mean accuracy of 84.6% ± 8.9% (up from 36.2% ± 10.4% at pre-test, d = 4.99), significantly outperforming Control participants who reached 54.8% ± 11.2% ($t(126) = 16.71$, $p < .001$, Cohen's d = 2.95).

Specifically, two-tier diagnostic item analysis showed that 89.4% of RBL students correctly explained the organic mass-loss concentration effect alongside BCR fraction redistribution, compared to only 38.7% of Control students. Furthermore, 86.4% of RBL learners accurately articulated how carboxyl and phenolic ligands in mature humic acids chelate divalent cations (such as Cu^{2+} and Pb^{2+}) into the oxidizable F3 fraction, whereas 81.8% correctly identified Cd and Zn as exhibiting higher residual mobility under mildly acidic conditions—insights directly grounded in their own laboratory extraction datasets.

Notably, gains in conceptual accuracy on the HMGCI correlated significantly with post-test scores on the Socio-Scientific Argumentation Rubric ($r = 0.74$, $p < .001$) and ECAS Systems-Thinking subscale ($r = 0.71$, $p < .001$) within the Experimental RBL cohort, indicating that mechanistic mastery of biogeochemical speciation directly underpinned students' capacity to formulate rigorous, evidence-based environmental policy recommendations.

Physicochemical maturity indicators further corroborated compost stabilization across the 60-day high-altitude process: final C/N ratios converged from 28.1 ± 1.2 to 13.4 ± 0.9 in T1 and from 27.3 ± 1.4 to 14.8 ± 1.1 in T2, electrical conductivity stabilized below 2.6 dS/m in T1 (avoiding salinity stress in sensitive Andean crops), and humic-to-fulvic acid ratios (HA/FA) increased more than threefold from 0.42 to 1.48, providing abundant macromolecular binding sites for trace-metal immobilization.

Element-specific geochemical trajectories documented by the student teams exhibited consistent thermodynamic and ligand-binding selectivity across all reactors: Cu displayed the strongest affinity for humic-acid complexation (oxidizable F3 fraction increasing from 34.2% at Day 0 to 64.8% at Day 60 in T1), followed by Pb (F3 + F4 combined reaching 88.4% at maturation) and Cr (predominantly partitioned in recalcitrant F3/F4 pools at 91.2%). By contrast, Zn and Cd maintained comparatively higher proportions in acid-soluble (F1) and Fe/Mn-oxide-bound (F2) fractions (combined F1+F2 of 38.6% for Zn and 33.4% for Cd in T1, versus 64.2% and 58.9% in unsorted T2), underscoring why source exclusion of batteries, galvanized hardware, and electronic scrap is essential for producing agronomically safe Andean compost.

4.3. Empirical Biogeochemical Findings Generated by Student Research Teams

A defining feature of the RBL intervention was that student teams generated authentic,

high-quality biogeochemical data characterizing high-Andean composting dynamics. Across all 14 insulated reactors, despite nocturnal ambient temperatures dropping to 1.5–4.0 °C, biological self-heating achieved thermophilic temperatures (>50 °C) within 6 to 9 days and sustained peak temperatures of 56.4–61.2 °C for 11 to 14 consecutive days, satisfying international pathogen sanitization criteria. Over the 60-day cycle, pH evolved from slightly acidic initial values (5.8 ± 0.3 in T1; 5.6 ± 0.4 in T2) to stabilized mildly alkaline levels at maturation (7.9 ± 0.2 in T1; 7.7 ± 0.3 in T2), accompanied by a 41.2% reduction in total organic matter.

BCR sequential extraction datasets produced by the student teams revealed striking contrasts between source-separated (T1) and unsorted (T2) municipal composts. While total dry-weight concentrations of Pb, Cd, Cu, Zn, and Cr increased by 24–38% from Day 0 to Day 60 in both treatments due to organic mass loss, their mobile exchangeable fractions (F1) declined substantially during humification. In source-separated T1 compost, the Mobility Factor (MF) decreased from 28.4% to 6.2% for Cu, from 19.6% to 4.1% for Pb, from 36.8% to 14.5% for Zn, and from 31.2% to 11.8% for Cd, with over 65% of Cu and Pb shifting into the stable organic-bound (F3) and residual (F4) fractions. Conversely, unsorted T2 compost retained significantly higher total metal burdens (exceeding Peruvian and FAO/WHO agricultural compost thresholds for Pb and Cd) and elevated bioavailable F1/F2 pools, resulting in a 34% reduction in quinoa seed germination index compared to T1 compost (94.2% germination index).

Correlation analyses across the 14 student-monitored reactors further confirmed strong inverse relationships between final compost pH and exchangeable metal mobility factors for Pb ($r = -0.84$, $p < .001$), Cu ($r = -0.81$, $p < .001$), and Zn ($r = -0.78$, $p < .001$), as well as significant positive correlations between humic-to-fulvic acid polymerization ratios and oxidizable F3 fraction sequestration ($r = 0.86$, $p < .001$). Students synthesized these empirical relationships into decision-support thresholds recommending source-separated municipal composting with a minimum 45-day maturation period prior to Andean tuber or grain crop application.

A fourth qualitative theme centered on emotional and civic empowerment. Several participants noted that prior to the RBL course, regional waste accumulation and mining- or urban-related trace metal pollution felt overwhelming and abstract; generating actionable empirical evidence that source separation reduces bioavailable Pb and Cu mobility by over 75% transformed passive eco-anxiety into constructive, evidence-informed environmental agency.

Crucially, comparative evaluation across the five trace elements established a clear mobility hierarchy in mature high-Andean municipal compost—Zn > Cd > Cu > Pb > Cr—mirroring international geochemical stability constants for organo-metallic humate complexes while quantifying the protective buffering capacity of alkaline pH stabilization and barley-straw bulking amendments (Smith, 2009; Hargreaves et al., 2008).

4.4. Qualitative Shifts in Epistemic Agency and Place-Based Pedagogical Identity

Thematic analysis of student reflective portfolios, laboratory logs, and focus group transcripts illuminated three interrelated qualitative mechanisms underlying these quantitative gains. First, students experienced a profound shift from passive reception to epistemic ownership: encountering unexpected experimental anomalies—such as slower thermophilic onset in poorly insulated reactors or higher Zn mobility in unsorted waste—prompted teams to consult primary geochemical literature and iteratively refine their explanatory models. As one pre-service biology teacher reflected during focus group interviews: 'Before this project, heavy metals were just symbols on a periodic table exam. When we extracted the exchangeable fraction from our own market compost and saw how quinoa germination responded, we understood why municipal waste separation is a chemical and social necessity.'

Second, learners developed sophisticated socio-scientific argumentation skills, moving away from binary 'compost is always safe' or 'waste is always toxic' positions toward nuanced, threshold-based risk reasoning grounded in source segregation and maturity indices. Third, pre-service teacher participants articulated concrete pedagogical transfer plans, designing inquiry-based secondary school modules utilizing low-cost bottle bioreactors, pH strips, and seed bioassays tailored to rural Andean schools.

Qualitative evidence further revealed that collaborative team roles—rotating responsibilities across field sampling, thermal monitoring, chemical digestion, statistical synthesis, and policy translation—strengthened academic self-efficacy and mutual accountability among female and rural-origin pre-service teachers who initially expressed apprehension toward quantitative analytical chemistry.

Focus group reflections confirmed that experiencing cognitive scaffolding firsthand—such as using visual concept maps to track metal partitioning across pH gradients—equipped pre-service educators with concrete diagnostic questioning techniques to uncover and address secondary students' misconceptions regarding pollution, decomposition, and soil fertility.

Analysis of the 38 lesson-design portfolios submitted by pre-service science teacher candidates in the Experimental RBL cohort revealed high fidelity in translating university-level biogeochemical concepts into age-appropriate, low-cost secondary school inquiry modules. Specifically, 92.1% of pre-service teachers incorporated structured investigative cycles (problem formulation, hypothesis testing, data graphing, and evidence-based argumentation) rather than cookbook verification labs, while 86.8% integrated local Andean agricultural soils, household organic waste sorting, and seed germination bioassays as accessible proxies for chemical toxicity and compost maturity.

4.5. Pedagogical Transfer: Pre-Service Teachers' High-Andean Inquiry Lesson Blueprints

Across the 38 secondary lesson designs, the highest-scoring pedagogical blueprints featured explicit diagnostic pre-assessments targeting common student misconceptions about decomposition, structured data-recording tables adapted to low-resource rural classrooms, and community action extensions—such as school-wide organic waste sorting campaigns and vegetable garden compost trials—demonstrating deep internalization of RBL principles.

5. Discussion

5.1. Bridging Disciplinary Biogeochemistry and Environmental Competency via RBL

The empirical findings of this study corroborate and extend international scholarship on Scientific Research-Based Learning and Socio-Scientific Issues pedagogy (Pedaste et al., 2015; Sadler, 2009; Freeman et al., 2014). By anchoring abstract environmental chemistry concepts—such as chemical speciation, ligand complexation, and cation exchange—within an authentic, student-led investigation of municipal solid waste composting, the RBL intervention overcame the persistent conceptual divide between declarative chemical knowledge and applied ecological judgment. Whereas traditional lecture-based instruction produced modest gains in factual recall while leaving core misconceptions regarding total versus bioavailable heavy metals largely intact, RBL fostered deep mechanistic reasoning evidenced by large effect sizes across both ECAS and HMGCI assessments.

Importantly, the structured five-phase scaffolding embedded in the intervention confirms Lazonder and Harmsen's (2016) synthesis demonstrating that guided inquiry maximizes learning gains in complex laboratory domains. Providing explicit training in BCR extraction protocols, quality-control blanks, and multivariate data visualization enabled undergraduate students and pre-service teachers to navigate analytical complexity without experiencing cognitive overload.

From a cognitive-learning standpoint, the marked reduction in the 'concentration-effect misconception' illustrates how direct manipulation of mass-balance equations alongside sequential fractionation resolves counterintuitive chemical phenomena (Linn et al., 2006; Smith, 2009). When students physically weighed reactor mass loss over 60 days and simultaneously observed declining exchangeable F1 percentages alongside rising total mg/kg concentrations, the distinction between total elemental concentration and chemical bioavailability became perceptually concrete rather than abstractly memorized.

In addition, these findings contribute to socio-scientific issues (SSI) scholarship by demonstrating that deep disciplinary mastery and civic-ethical reasoning are mutually reinforcing rather than competing curricular priorities (Zeidler et al., 2019; Sadler, 2009). Students who achieved the strongest gains in chemical fractionation interpretation simultaneously produced the most sophisticated, nuanced municipal policy recommendations—balancing agronomic nutrient recovery against precautionary heavy-metal loading thresholds.

Furthermore, the convergence of conceptual gains on the HMGCI and argumentation quality on the socio-scientific rubric underscores the role of epistemic emotions—such as curiosity, productive surprise upon encountering anomalous pH or metal mobility readings, and intellectual satisfaction when resolving experimental puzzles—in sustaining deep cognitive engagement throughout semester-long inquiry (Linn et al., 2006; Freeman et al., 2014).

5.2. Pedagogical Value of High-Andean Place-Based Inquiry

This investigation further highlights the transformative potential of place-based environmental education in high-altitude Andean contexts (Gruenewald, 2003; Semken & Freeman, 2008). Designing insulated composting reactors capable of sustaining thermophilic bio-oxidation despite sub-zero Andean nights required students to integrate thermodynamics, microbial ecology, and local material knowledge (such as utilizing native ichu grass for thermal insulation). Furthermore, linking chemical fractionation results directly to local agricultural crops (quinoa and radish) and municipal waste governance bridged university science with community livelihoods, validating students' cultural identities while cultivating actionable sustainability competencies (Wiek et al., 2011; UNESCO, 2020).

Furthermore, integrating bilingual scientific vocabulary (Spanish, Quechua, and English) alongside ancestral Andean ecological concepts—such as ayni (reciprocity) and soil nurturing (allpa uyway)—deepened epistemic engagement among first-generation and rural students (Apffel-Marglin, 1998; Semken & Freeman, 2008). Rather than positioning Western analytical chemistry in opposition to Indigenous agroecological knowledge, the RBL framework fostered productive dialogue between empirical geochemical monitoring and traditional Andean stewardship of soil fertility.

Moreover, the high-altitude Andean context illuminated critical socio-economic dimensions of municipal solid waste management. By conducting primary waste audits in municipal markets and interviewing local farmers, pre-service teachers recognized that technical composting solutions cannot succeed in isolation from household source-separation incentives, municipal collection logistics, and farmer trust in compost quality certification (Farrell & Jones, 2009; Hoornweg & Bhada-Tata, 2012).

In addition, our findings resonate with critical pedagogy of place (Gruenewald, 2003) by illustrating how scientific investigation can simultaneously advance decolonization—challenging imported, context-blind laboratory templates—and reinhabitation, empowering Andean youth and future educators to care for local watersheds and agricultural soils through rigorous, community-accountable science.

5.3. Implications for Science Teacher Education and Curriculum Reform

For initial teacher education (ITE) and university environmental science programs, our findings underscore the imperative of embedding authentic, locally relevant research experiences into core disciplinary courses rather than isolating research methods into a final-year thesis seminar (Healey & Jenkins, 2009; Brew, 2013). When pre-service science educators experience the full cycle of environmental inquiry—from community waste auditing to analytical interpretation and policy communication—they develop both the conceptual mastery and the pedagogical self-efficacy necessary to implement inquiry-based sustainability education in resource-constrained schools (Florian & Spratt, 2013; Hattie, 2009).

At the policy and institutional level, universities and ministries of education across Latin America should foster formal partnerships between teacher education faculties, environmental engineering laboratories, and municipal waste authorities. Establishing shared university–municipality environmental monitoring observatories creates sustainable living laboratories where students generate valuable baseline data on municipal compost quality while municipalities gain evidence-based guidance on source-separation ordinances.

Teacher education faculties should also redesign science teaching practicum rubrics to explicitly reward pre-service educators who co-design place-based socio-scientific investigations with local communities, municipalities, and Indigenous or campesino agricultural associations (Gruenewald, 2003; Florian & Beaton, 2018). Establishing regional networks of RBL-trained science teachers facilitates peer mentoring, open-access sharing of calibrated composting protocols, and sustained pedagogical innovation across geographically dispersed Andean provinces.

Furthermore, institutionalizing interdisciplinary co-teaching partnerships—where analytical chemists, soil scientists, and science education specialists collaboratively mentor pre-service teachers—overcomes the traditional disciplinary silos that often isolate laboratory instrumentation from pedagogical design.

At the curricular architecture level, accrediting bodies and university academic councils should recognize authentic student-led environmental monitoring projects as valid alternatives to traditional closed-book laboratory exams, embedding competency-based portfolios and community-engaged research credits across undergraduate teacher education pathways (Brew, 2013; Wiek et al., 2011).

At the classroom assessment level, teacher educators should replace single-shot summative exams with multi-stage research rubrics that evaluate hypothesis plausibility, metrological rigor, collaborative troubleshooting, and culturally responsive science communication—thereby rewarding the full spectrum of investigative and civic competencies essential for twenty-first-century science teaching (Lederman et al., 2014; Rieckmann, 2018).

5.4. Limitations and Directions for Future Research

Several methodological limitations warrant consideration when interpreting these findings. First, the quasi-experimental design utilized intact university course sections within a single high-Andean institution, which may constrain generalizability to other ecological zones or secondary school settings. Second, while the 16-week intervention captured immediate semester-long competency and conceptual gains, longitudinal follow-up is needed to assess whether pre-service teachers sustain inquiry-based environmental practices upon entering full-time classroom teaching. Future research should implement multi-site longitudinal designs across diverse Andean and coastal ecosystems, incorporate ICP-MS multi-elemental profiling alongside microbial metagenomics, and evaluate downstream learning outcomes among secondary school pupils taught by RBL-trained educators.

In addition, future investigations should examine the cost-effectiveness and institutional scalability of low-cost analytical surrogates—such as portable X-ray fluorescence (pXRF), colorimetric test strips, and standardized phytotoxicity bioassays—paired with centralized university reference laboratories so that rural Andean secondary schools can replicate RBL composting inquiries without prohibitive laboratory budgets.

Methodologically, future studies should also incorporate delayed post-tests (6 to 12 months post-intervention) and classroom observation protocols during pre-service teachers' school

practicums to verify longitudinal retention of geochemical concepts and transfer of RBL scaffolding strategies into secondary school science lessons.

Specifically, scaling RBL-anchored environmental monitoring networks across regional Andean universities and teacher-training institutes (Institutos de Educación Superior Pedagógica) can generate open-access municipal soil and compost quality atlases while continuously updating pre-service science curricula with locally validated empirical datasets.

6. Conclusion

Scientific Research-Based Learning provides a powerful, empirically validated pedagogical framework for cultivating multidimensional environmental competencies and deep geochemical understanding of heavy metal mobility during municipal solid waste composting in high-Andean contexts. By engaging pre-service science educators and environmental students in the complete cycle of contextual problematization, reactor engineering, sequential chemical fractionation, phytotoxicity testing, and community policy communication, RBL transforms abstract environmental chemistry into meaningful epistemic and civic agency. Institutionalizing place-based biogeochemical inquiry within higher education and teacher preparation curricula represents a vital pathway toward advancing circular-economy practices, soil safety, and equitable sustainability education across Andean communities and beyond.

Ultimately, aligning science teacher preparation with authentic biogeochemical inquiry empowers a new generation of Andean educators to serve as catalytic knowledge brokers between university laboratories, municipal environmental governance, and rural agricultural communities, fostering resilient socio-ecological futures grounded in empirical rigor and cultural reciprocity.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Pedro Liberato Valladares Jara: Conceptualization, Methodology, Investigation, Writing – original draft, Project administration. Maximiliano Loarte Rubina: Conceptualization, Formal analysis, Biogeochemical validation, Writing – review & editing. Kiko Felix Depaz Celi: Methodology, Pedagogical design, Data curation, Statistical analysis, Writing – review & editing. Francisco Claudio Leon Huerta: Investigation, Supervision, Critical revision, Validation, Writing – review & editing.

DECLARATION OF COMPETING INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

ETHICS STATEMENT

This study was approved by the Institutional Research Ethics Committee (Protocol CIEI-2025-048), and written informed consent was obtained from all student participants.

DATA AVAILABILITY

Anonymized assessment datasets and composting physicochemical records generated during the current study are available from the corresponding author upon reasonable academic request.

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