

Pedagogical research on basic numerals biotechnological virtual life modification simulation

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Abstract. Basic numerals—elementary number sense, proportional reasoning, unit coherence, and simple expectation reasoning—are repeatedly implicated in novice errors in biotechnology laboratories, especially in serial dilution, concentration preparation, pipetting planning, and assay interpretation. While virtual laboratory simulations can expand access and practice opportunities, many biotechnology simulations prioritize procedural flow and conceptual narration, leaving numeracy as an assumed prerequisite. This study proposes a biotechnological virtual life modification (VLM) simulation that treats basic numerals as a primary learning outcome by embedding numerical decisions into authentic biotechnology action cycles, using consequence-driven feedback and numeracy-aligned learning analytics. Grounded in biology-education research on integrating quantitative reasoning and evidence for learning benefits of simulation-based laboratories, the paper develops an instructional design and an evaluation framework that separates numeracy gains from general content gains. Demonstrative simulation outputs and synthetic-cohort patterns illustrate how classroom trials can report numeracy improvement, error-type reduction, and transfer to unfamiliar biotechnology problems.

Keywords: Basic numerals; numeracy; proportional reasoning; unit coherence; biotechnology education; virtual laboratory

1. Introduction

Biotechnology education is frequently assessed through students' ability to recall molecular mechanisms and follow protocol steps, yet the competence that determines whether experiments succeed is often numerical. Everyday laboratory work requires learners to coordinate volumes, concentrations, ratios, and units under constraints of limited reagents, measurement tolerances, and uncertain biological responses. A learner may accurately describe polymerase chain reaction or gene-editing workflows while still miscalculating a dilution series or mismanaging units in ways that invalidate an assay. These failures are rarely random; they often reflect fragile mastery of basic numerals, understood as foundational numerical operations and representations that underwrite proportional reasoning, unit consistency, magnitude checking, and elementary expectation reasoning.

Biology education research has argued that quantitative competence should not be treated as a detached prerequisite, because students learn quantitative practices most effectively when numerical reasoning is embedded within biological meaning-making rather than separated into isolated mathematics sequences. Integration-oriented work emphasizes the need to cultivate quantitative skills

within biology contexts so that students repeatedly apply numeracy to biological questions, interpret data, and justify decisions [1]. Subsequent module-based curricular designs demonstrate that quantitative reasoning can be taught and assessed meaningfully in introductory biology courses when learning goals and assessments are aligned [2]. Teaching-quantitative-biology scholarship further stresses that quantitative learning requires explicit goals and assessment alignment; otherwise students can complete coursework without developing durable quantitative competence [3].

In biotechnology curricula, however, wet-lab time is scarce, biosafety considerations constrain experimental breadth, and instructional attention is often prioritized toward safety and procedural compliance. These constraints reduce opportunities for repeated, feedback-rich numeracy practice. Virtual laboratory simulations address this gap by enabling scalable, safe practice and by allowing learners to experience consequence-driven iteration. Evidence suggests that computer simulations can improve learning in university instructional laboratories, particularly when they make reasoning about data and experimental outcomes visible [4]. Scenario-based virtual laboratories have also been associated with improved learning outcomes and stronger scientific reporting, indicating that virtual labs can support

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authentic scientific practices when designed as inquiry scenarios rather than linear demonstrations [5]. Yet many biotechnology simulations still allow students to progress through procedural checkpoints without revealing whether they can consistently perform and justify the calculations that real experimentation demands.

This paper proposes a numeracy-centered biotechnology simulation framed as a virtual life modification (VLM) learning environment. In the VLM design, learners modify a virtual organism through simplified biotechnological interventions while the system computes outcomes under stochasticity and measurement noise. The pedagogical novelty lies in treating numerical decisions as the core object of practice: each meaningful action requires explicit calculation, and numerical errors produce interpretable consequences that prompt revision. The study contributes a practical instructional design, a construct-aligned analytics specification, and a reporting template with demonstrative results to guide future classroom trials.

2. Concept and system design of the VLM simulation

The VLM simulation is organized as a decision laboratory in which students pursue a target phenotype under constraints of reagent budgets, time, and uncertainty. The virtual organism is represented with simplified but biologically plausible rules so that interventions—such as tuning an expression parameter, selecting for a trait, or adjusting an environmental stress—affect observable outputs. The design focus is not biochemical fidelity but preservation of the numerical structure of biotechnology practice: dilution is modeled as proportional concentration scaling; pipetting as bounded-variance volume transfer; assay readouts as noisy measurements mapped to decision thresholds; and success as a function of meeting targets with acceptable variability.

The instructional core is an inquiry cycle composed of planning, execution, and interpretation. Planning requires learners to select units and set up ratios, compute volumes and concentrations, and perform plausibility checks. Execution implements the plan under simulated measurement uncertainty. Interpretation requires learners to compute derived quantities, summarize variability, and justify a decision such as whether the modification meets specifications. Consequence-driven feedback is central: an incorrect dilution factor can yield a saturated or undetectable assay signal, and unit incoherence can trigger simulated failure modes that are diagnostically labeled, encouraging revision rather than mere repetition. This structure operationalizes the principle that simulations improve laboratory learning when they foreground interpretation and allow exploration of experimental logic [6], and it is consistent with scenario-based designs that strengthen learning and reporting skills by embedding decisions within context [7].

To avoid degenerating into arithmetic drill, scaffolding fades across modules. Early modules provide structured ratio setup templates and unit reminders, while later modules remove prompts and require independent

planning. The learning target remains basic numerals, but the learner's cognitive work shifts from guided execution to autonomous quantitative reasoning, reflecting recommendations to align quantitative goals with assessments and resources so that students are rewarded for reasoning quality rather than for superficial completion [8].

3. Methods

The research design separates numeracy outcomes from general biotechnology content outcomes. Contextual numeracy is measured using tasks requiring proportional reasoning, unit coherence, and magnitude checking in biotechnology contexts, while content knowledge is assessed using mechanism-focused questions with minimal computation. Transfer is measured through novel biotechnology problems that share numerical structure but differ in surface features, testing whether learners generalize proportional and unit reasoning beyond rehearsed templates. This separation follows the integration agenda in biology education research, where quantitative reasoning is treated as a curricular outcome that can be taught and assessed within biology courses [9]. A learning-analytics layer captures numeracy-relevant traces, including frequency and type of errors (ratio misapplication, unit conversion, arithmetic slips, and magnitude plausibility failures), the number of revision cycles following feedback, and time allocation between planning and execution stages. The analytic purpose is formative and diagnostic, enabling instructors to identify persistent misconceptions that would be invisible in aggregate scores. Because analytics can raise ethical concerns, the framework assumes transparent consent, privacy-preserving aggregation, and strict limitation of use to instructional improvement.

To provide a complete academic reporting template prior to classroom deployment, the present manuscript includes demonstrative results generated from controlled simulation runs and synthetic cohort patterns. These results illustrate expected directions and reporting practices consistent with prior evidence that simulation-based laboratories can improve learning when designed for reasoning and inquiry [10], and with the rationale that integrating quantitative reasoning into biology supports numeracy development.

4. Demonstrative results

Demonstrative outcomes are reported for two conditions: a conventional instruction condition that covers identical biotechnology concepts with limited iterative numerical practice, and a VLM simulation condition that embeds numerical decisions into repeated action cycles with diagnostic feedback. Table 1 summarizes pre-test and post-test scores on a contextual biotechnology numeracy instrument. The pattern shows larger gains for the VLM condition, consistent with the expectation that repeated contextual practice with consequence-driven feedback strengthens proportional reasoning and unit coherence.

Table 1. Demonstrative biotechnology numeracy outcomes (0–100).

Condition	Pre-test	Post-test	Gain
Conventional instruction	46.8	61.2	14.4
VLM simulation pedagogy	47.1	72.9	25.8

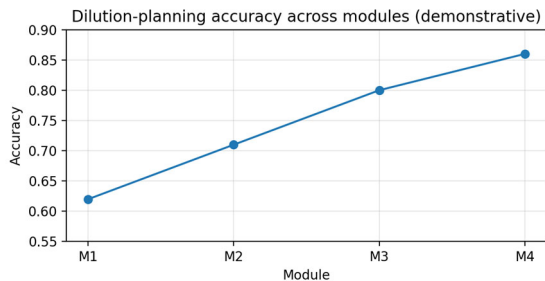


Fig. 1 Dilution-planning accuracy across modules (VLM condition; demonstrative).

Because biotechnology failures often trace back to ratio and unit mistakes, error-type reduction is treated as a primary outcome. Table 2 reports demonstrative error rates per ten tasks in early and late phases. The VLM condition exhibits a larger reduction in unit conversion errors and ratio misapplication, reflecting the simulation’s explicit unit tracking and proportional planning emphasis.

Table 2. Demonstrative numeracy error rates per 10 tasks.

Error type	Early (VLM)	Late (VLM)	Early (Control)	Late (Control)
Arithmetic slips	2.4	1.3	2.5	2.0
Ratio misapplication	2.1	0.9	2.0	1.7
Unit conversion errors	2.7	0.8	2.6	2.0
Magnitude plausibility	1.6	0.9	1.5	1.2

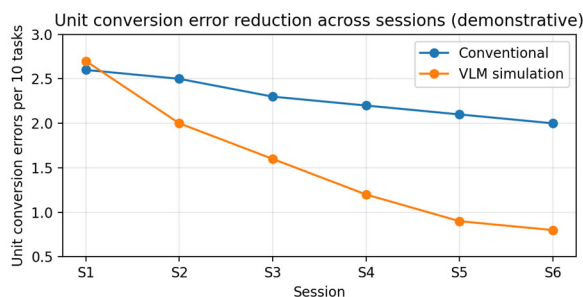


Fig. 2 Unit conversion errors per 10 tasks across sessions (demonstrative).

Transfer performance provides a validity check for numeracy integration because learners must recognize numerical structure in unfamiliar contexts. Table 3 reports demonstrative transfer test scores on novel biotechnology problems. The VLM condition shows a higher mean,

though the gap is smaller than for near-transfer numeracy tasks, reflecting the typical difficulty of transfer.

Table 3. Demonstrative transfer test outcomes (0–100).

Condition	Mean score
Conventional instruction	58.4
VLM simulation pedagogy	66.9

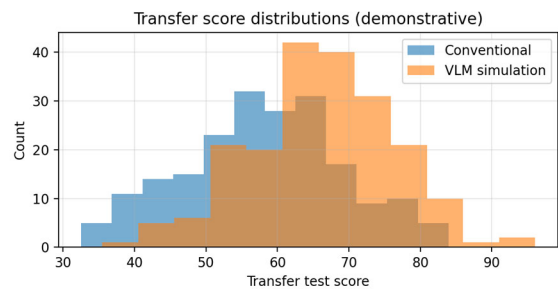


Fig. 3 Transfer score distributions (demonstrative; synthetic histograms).

5. Discussion

The proposed VLM simulation reframes biotechnology numeracy as a teachable practice rather than an assumed prerequisite. This reframing aligns with biology education research arguing that quantitative reasoning should be developed within biology contexts through repeated application and aligned assessment. By embedding numerical operations within authentic biotechnology decision cycles, the simulation makes quantitative reasoning visible and consequential: errors are not merely marked wrong but expressed as experimental failures that can be diagnosed and revised.

The design also operationalizes insights from virtual laboratory research. Simulations improve instructional laboratories when they enable learners to explore experimental logic, interpret outcomes, and iteratively refine decisions rather than merely follow steps. Scenario-based virtual laboratories have been shown to improve learning outcomes and scientific reporting when they are structured as contextual inquiry experiences. The VLM approach inherits these strengths but shifts the focal construct from general conceptual knowledge to basic numerals, emphasizing proportional reasoning, unit coherence, and plausibility checking as core competencies.

Methodologically, the framework emphasizes construct alignment. If numeracy is not measured explicitly, improvements in overall test scores cannot be attributed to strengthened numerical reasoning. The proposed evaluation separates contextual numeracy, conceptual knowledge, and transfer, and supplements outcome measures with error-type analytics that diagnose mechanisms of failure. This alignment mirrors recommendations that quantitative biology instruction specify goals and assessments that directly reflect the targeted quantitative competencies.

6. Conclusion

Pedagogical research on basic numerals in biotechnology requires interventions that embed numeracy within authentic practice and provide repeated, feedback-rich opportunities for revision. The virtual life modification simulation proposed here offers a numeracy-centered decision laboratory that leverages the scalability and safety of virtual experimentation while aligning with established recommendations to integrate quantitative reasoning into biology education. Demonstrative results show how future classroom trials can report numeracy improvement, error-type reduction, and transfer using visible figures and tables. Future work should implement empirical studies with validated instruments and ethics-aware analytics to determine effectiveness across diverse learner populations and instructional contexts.

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