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How do students understand biological concepts? A study on science literacy in basic education

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Abstract

This analysis investigates how students in basic education comprehend biological concepts, examining cognitive processes and pedagogical factors shaping science literacy development. Drawing on contemporary research, this study analyzes mechanisms through which elementary and junior secondary students construct understanding of fundamental biological principles including cellular processes, heredity, ecosystems, and human physiology. The analysis reveals that students' comprehension operates through complex interactions between prior knowledge, developmental readiness, and instructional experiences. Research demonstrates that learners frequently maintain persistent misconceptions regarding biological phenomena, rooted in intuitive reasoning and everyday observations conflicting with scientific explanations. These alternative conceptions prove resistant to traditional instruction, necessitating conceptual change pedagogies explicitly addressing cognitive conflicts. The study identifies inquiry-based learning, hands-on experimentation, and culturally responsive instruction as particularly effective for facilitating robust understanding. Furthermore, authentic science literacy encompasses not merely factual knowledge but critical thinking competencies and abilities to apply biological concepts in analyzing real-world issues. Challenges emerge in linguistically diverse contexts where students navigate science instruction in second languages while reconciling scientific concepts with indigenous knowledge systems. This analysis concludes that enhancing biological concept comprehension requires pedagogical innovations systematically addressing misconceptions, leveraging experiential knowledge, integrating culturally relevant contexts, and cultivating higher-order cognitive capabilities essential for scientifically literate citizenship.

Keywords

biological concepts, science literacy, conceptual understanding, misconceptions, basic education, inquiry-based learning

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Introduction

The imperative to cultivate scientifically literate citizens has intensified as contemporary societies navigate increasingly complex challenges requiring biological understanding—ranging from pandemic disease management and climate change adaptation to biotechnology ethics and biodiversity conservation (Bybee, 2020; Feinstein et al., 2013). Biology education occupies a particularly consequential position within scientific literacy development, providing conceptual frameworks essential for comprehending life processes, ecological interdependencies, evolutionary dynamics, and human health phenomena that fundamentally shape individual and collective well-being (Duit et al., 2012). Understanding how students in basic education—the foundational stratum where scientific thinking patterns and conceptual frameworks are established—comprehend biological concepts therefore constitutes not merely an academic concern but a societal imperative with profound implications for public health literacy, environmental stewardship, and informed democratic participation in science-policy deliberations.

Despite decades of educational research, curriculum reform initiatives, and pedagogical innovation, substantial evidence demonstrates that students across diverse educational contexts struggle to develop robust understanding of fundamental biological principles. International comparative assessments including the Programme for International Student Assessment (PISA) and Trends in International Mathematics and Science Study (TIMSS) consistently reveal concerning deficiencies in students' biological concept comprehension, scientific reasoning capabilities, and abilities to apply knowledge in novel contexts (OECD, 2019; Mullis et al., 2020). These deficits persist not merely as superficial knowledge gaps but manifest as deeply rooted misconceptions that resist instructional intervention, constrain subsequent learning trajectories, and persist even among university biology majors (Coley & Tanner, 2015). Elucidating the cognitive mechanisms underlying biological concept acquisition, identifying pedagogical approaches most efficacious in facilitating conceptual change, and recognizing contextual factors mediating comprehension processes therefore constitute urgent research priorities with significant practical implications for educational practice and curriculum design.

Contemporary understanding of how students comprehend biological concepts is grounded in constructivist learning theories emphasizing that knowledge acquisition represents an active construction process wherein learners interpret new information through existing cognitive schemas rather than passively absorbing transmitted facts (Piaget, 1964; Vygotsky, 1978). Students approach biological instruction equipped with pre-existing mental frameworks—organized knowledge structures derived from everyday experiences, cultural contexts, and prior educational encounters—that fundamentally shape how new biological information is interpreted, integrated into existing understandings, or rejected as inconsistent with established beliefs (Chi et al., 1994).

These prior knowledge structures, frequently characterized as "naïve theories," "intuitive frameworks," or "folk biology," exert powerful influences on learning trajectories, sometimes facilitating comprehension when aligned with scientific concepts but often generating persistent misconceptions when contradicting formal biological principles (Carey, 1985). Research in cognitive psychology and science education demonstrates that students' intuitive biological reasoning often diverges substantially from scientifically accepted explanations, reflecting cognitive heuristics optimized for everyday functioning but fundamentally incompatible with scientific biological thinking (Coley & Tanner, 2015). For instance, teleological reasoning patterns—wherein students attribute purposeful design and intentionality to biological structures and processes—persist across developmental stages despite evolutionary biology's emphasis on natural selection operating without conscious direction (Kelemen et al., 2019). Similarly, anthropomorphic reasoning, whereby learners ascribe human-like intentions and consciousness to organisms and biological systems, represents another pervasive cognitive tendency conflicting with mechanistic scientific explanations (Tamir & Zohar, 1991).

Extensive empirical investigations document the pervasive nature and remarkable persistence of biological misconceptions across diverse content domains and student populations. Regarding cellular biology, recent research by Strgar (2021) revealed that secondary students maintain substantial confusion regarding cellular structure, organelle functions, and metabolic processes, particularly concerning energy transformation mechanisms in photosynthesis and cellular respiration. Students frequently conceptualize cells anthropomorphically, attributing intentional decision-making to cellular components, and struggle to comprehend molecular mechanisms underlying macroscopic biological phenomena—reflecting difficulties bridging microscopic and macroscopic explanatory levels (Duncan et al., 2023).

Genetic and hereditary concepts present particularly formidable comprehension challenges. Seminal work by Mills Shaw et al. (2008) documented widespread misconceptions regarding DNA structure, gene function, and inheritance patterns among adolescent learners, with students exhibiting difficulties distinguishing genotype from phenotype, misunderstanding probabilistic inheritance mechanisms, and harboring deterministic views of genetic causation. More recent research by Duncan et al. (2023) corroborates these persistent comprehension difficulties, demonstrating that even following targeted genetics instruction, students maintain alternative conceptions regarding genetic information flow, gene expression regulation, and the relationship between genes and traits.

Ecological concepts similarly engender substantial comprehension obstacles. Research by Kelemen et al. (2019) revealed that students across elementary through secondary levels struggle with ecosystem dynamics, energy flow, and biogeochemical cycling, frequently conceptualizing ecosystems through simplistic linear food chain models rather than complex food web networks characterized by reciprocal interdependencies. Students exhibit particular difficulty comprehending decomposition processes, nutrient cycling mechanisms, and thermodynamic principles underlying energy dissipation across trophic levels (Leach et al., 1996). Additionally, evolutionary concepts remain profoundly misunderstood, with learners harboring teleological misconceptions attributing adaptive changes to organisms' intentional responses to environmental pressures rather than natural selection operating on random genetic variation across populations and generations (Gregory, 2009).

Biological concept comprehension is mediated by students' cognitive developmental stages, with research demonstrating that abstract biological principles—particularly those involving microscopic phenomena invisible to direct observation, probabilistic rather than deterministic causation, and extended temporal scales exceeding human experiential timeframes—pose substantial challenges for elementary and early secondary learners whose cognitive capabilities remain predominantly concrete operational (Inhelder & Piaget, 1958). Songer and Mintzes (1994) documented developmental progressions in biological reasoning, establishing that younger students exhibit greater reliance on perceptually based reasoning and struggle to comprehend processes operating beyond observable scales, while older students gradually develop capacities for abstract reasoning enabling engagement with molecular mechanisms and evolutionary timeframes spanning millions of years.

Language proficiency constitutes another critical mediating variable influencing biological comprehension. Biology education's specialized vocabulary, polysemous terms carrying distinct meanings in everyday versus scientific contexts (e.g., "theory," "adaptation," "respiration"), and extensive use of metaphorical language potentially generate or reinforce misconceptions (Wellington & Osborne, 2001). Research by Yore et al. (2003) established that students' science literacy development depends substantially on linguistic competencies enabling comprehension of technical terminology, interpretation of visual representations including diagrams and graphs, and engagement with multimodal scientific texts integrating verbal and visual information systems.

Contemporary research increasingly emphasizes that traditional didactic instruction—characterized by teacher-centered knowledge transmission, emphasis on factual memorization, and limited student cognitive engagement—proves insufficient for facilitating robust biological concept comprehension, particularly regarding transformation of deeply rooted misconceptions (Duit et al., 2012). Conceptual change pedagogy, grounded in cognitive conflict theory, advocates systematically surfacing students' alternative conceptions, creating cognitive dissonance through confrontation with contradictory empirical evidence or logical inconsistencies, and supporting reconstruction of scientifically aligned conceptual frameworks through scaffolded reasoning processes (Posner et al., 1982). Meta-analytic reviews by Duit et al. (2012) demonstrate that instructional approaches incorporating explicit misconception identification, conceptual conflict creation, and extended engagement with anomalous evidence yield significantly superior learning outcomes compared to conventional transmission-oriented pedagogy.

Inquiry-based learning approaches, wherein students engage in authentic scientific investigation processes including question formulation, hypothesis development, experimental design, data collection and analysis, and evidence-based conclusion construction, have demonstrated considerable efficacy in promoting both biological content knowledge acquisition and scientific reasoning skill development (National Research Council, 2012). Research synthesis by Minner et al. (2010) established that inquiry instruction positively impacts learning outcomes, particularly when incorporating substantial student autonomy in investigation design, sustained engagement with phenomena over extended timeframes, and explicit connections between investigative activities and target conceptual understandings.

Furthermore, culturally responsive science pedagogy—instructional approaches recognizing and leveraging students' cultural backgrounds, indigenous knowledge systems, and community contexts as productive resources for scientific learning rather than obstacles to overcome—demonstrates promise for enhancing engagement and conceptual development, particularly in linguistically and culturally diverse educational settings (Aikenhead & Elliott, 2010). Research by Bang and Medin (2010) demonstrated that acknowledging and respectfully exploring relationships between indigenous ecological knowledge and Western scientific biology facilitates deeper conceptual understanding while validating students' cultural identities and challenging deficit perspectives that position non-Western knowledge systems as inferior or irrelevant to scientific learning.

Despite substantial scholarship examining biological concept comprehension, significant research gaps persist with important implications for educational practice. First, existing literature disproportionately derives from Western, predominantly Anglophone educational contexts, with insufficient attention to how linguistic diversity, multilingual science instruction, and non-Western cultural epistemologies shape biological understanding (Cobern & Aikenhead, 1998). Second, limited research systematically examines intersections between students' everyday experiential knowledge—particularly in contexts characterized by rich biodiversity and traditional ecological practices—and formal biological concept acquisition trajectories. Third, insufficient longitudinal investigation traces conceptual development across elementary through secondary education, limiting understanding of sensitive periods when particular misconceptions emerge, critical junctures when conceptual change interventions prove most efficacious, and developmental trajectories characterizing progression toward sophisticated biological reasoning.

Within Indonesian educational contexts specifically, these gaps assume particular significance given unique challenges and opportunities characterizing biology education. Indonesian students navigate science instruction frequently delivered in Bahasa Indonesia—the national language—while many speak regional languages as primary communicative media, creating potential linguistic barriers to biological concept comprehension and science literacy development (Lie, 2007). Additionally, Indonesia's extraordinary biodiversity—comprising megadiverse ecosystems spanning tropical rainforests, coral reefs, and endemic species—and rich traditions of indigenous ecological knowledge present unique opportunities for contextualized biology instruction connecting formal scientific concepts with students' lived environmental experiences, yet limited research explores pedagogical approaches leveraging these resources (Suastra & Yasmini, 2013). Furthermore, Indonesia's PISA performance in science literacy consistently ranks substantially below international averages and neighboring Southeast Asian nations, signaling considerable challenges in biological concept comprehension requiring systematic investigation and evidence-based intervention (OECD, 2019).

These empirical and conceptual lacunae necessitate comprehensive analysis examining how students in basic education comprehend biological concepts, particularly attending to cognitive mechanisms, pedagogical approaches, and contextual factors operating across diverse educational landscapes. This analysis endeavors to address these gaps through systematic examination of contemporary research literature, guided by the following research questions:

- What cognitive processes, developmental factors, and prior knowledge structures mediate students' comprehension of fundamental biological concepts across content domains including cellular biology, genetics, ecology, and human physiology, and how do these mechanisms vary across developmental stages in basic education?
- What specific misconceptions regarding biological phenomena do students most commonly harbor across different content areas, what cognitive and experiential sources generate and sustain these alternative conceptions, and through what mechanisms do they persist despite formal instructional intervention?
- Which pedagogical approaches—including inquiry-based learning, conceptual change instruction, hands-on experimentation, and culturally responsive pedagogy—demonstrate greatest efficacy in facilitating robust biological concept comprehension

and science literacy development, and what instructional design principles characterize effective interventions?

- What implications emerge for instructional practice, curriculum design, assessment approaches, and teacher professional development regarding enhancing students' biological concept understanding and cultivating authentic science literacy competencies encompassing not merely factual knowledge but critical thinking, scientific reasoning, and real-world application capabilities?

By systematically addressing these questions through integrative analysis of contemporary empirical research and theoretical frameworks, this study seeks to contribute nuanced understanding of biological concept comprehension processes in basic education while identifying evidence-based pedagogical strategies for enhancing science literacy development across diverse educational contexts.

Cognitive, developmental, and knowledge factors in learning fundamental biological concepts

Students' comprehension of fundamental biological concepts—spanning cellular biology, genetics, ecology, and human physiology—is shaped by the interplay of cognitive processes, developmental factors, and prior knowledge structures. These mediators determine how learners conceptualize complex biological phenomena, integrate new information, and construct scientifically coherent understanding across developmental stages.

Cognitive processes and conceptual structuring

Cognitive processes such as abstraction, categorization, and metacognition play a central role in biology learning. Students often progress from concrete reasoning to abstract conceptualization as they move through elementary and secondary education (Paidi, Mercuriani, & Subali, 2020). In cellular biology and genetics, learners initially interpret cells or genes through visible or tangible analogies—such as "cells as tiny organisms" or "genes as traits"—before understanding them as abstract functional systems (Coley & Tanner, 2012). Misconceptions often arise from domain-general reasoning biases, such as essentialist or teleological thinking, which lead learners to attribute purpose or inheritance mechanisms inaccurately (Nehm, 2019). Cognitive restructuring through inquiry, argumentation, and metacognitive reflection allows students to replace naïve models with scientifically valid frameworks (Martin, Mintzes, & Clavijo, 2000).

Developmental factors and conceptual progression

Developmental theories, including Fischer's dynamic skill theory and Piagetian cognitive stages, suggest that comprehension in biology evolves through hierarchical coordination of representational systems (Fischer & Silvern, 1985). Younger learners in primary education typically function at the concrete operational stage, relying on perceptual cues and direct experiences—favoring topics such as observable life cycles or basic human anatomy (Hinton & Fischer, 2011). As students enter adolescence, formal operational reasoning emerges, allowing abstract interpretation of molecular interactions, ecological systems, and genetic probabilities (Tasci & Yurdugul, 2017). At this stage, learners integrate cross-domain

principles, such as energy flow or cellular regulation, indicating the development of hierarchical conceptual coherence across biology domains (Nehm, 2019).
Developmental differences also influence the ability to connect scales of biological organization—from molecular to ecological. Primary students tend to compartmentalize topics (e.g., "plants" vs. "animals"), while secondary students begin to perceive systemic interdependence among biological levels (Paidi et al., 2020). Instructional scaffolds that bridge micro- and macro-level phenomena are therefore critical for developing integrative thinking.

Prior knowledge and conceptual change

Prior knowledge acts as both a foundation and a barrier to biological understanding. Learners' preconceptions, often drawn from everyday experiences, guide initial interpretation but can constrain comprehension if not aligned with scientific models. Tsai and Huang (2001) found that students learning about biological reproduction often relied on intuitive, anthropomorphic reasoning, demonstrating limited transfer across content domains. Instruction emphasizing conceptual change theory—in which misconceptions are elicited, confronted, and reconstructed—has been shown to enhance biological literacy and long-term retention (Martin et al., 2000).

Variation across developmental stages

Across developmental stages in basic education, variations in cognitive maturity, metacognitive regulation, and epistemic beliefs shape how students engage with biological content. Early learners benefit from hands-on, inquiry-based learning that anchors abstract ideas in observable phenomena (Paidi et al., 2020). Middle and secondary students, possessing greater working memory and inferential reasoning capacity, can engage in model-based reasoning and cross-conceptual integration. However, without explicit instruction in scientific reasoning, even advanced learners may revert to intuitive, domain-specific misconceptions (Coley & Tanner, 2012). Thus, pedagogical alignment with developmental readiness—progressing from experiential exploration to abstract modeling—is essential for fostering deep, transferable understanding.

In summary, comprehension of biological concepts is mediated by cognitive processing abilities, developmental readiness, and the restructuring of prior knowledge. Students' movement from perceptual to conceptual reasoning mirrors developmental and epistemological growth. Effective biology education must therefore scaffold learning through progressively complex cognitive engagement, contextualized instruction, and explicit metacognitive reflection. Integrating cognitive science insights with developmental pedagogy ensures that learners not only memorize facts but also construct enduring, interconnected models of living systems.

Persistent misconceptions in biology: Cognitive and experiential foundations

Students' misconceptions about biological phenomena are among the most documented challenges in science education. These misconceptions—often termed *alternative conceptions*—arise from intuitive reasoning, experiential biases, and cognitive constraints, persisting even after formal instruction. They are not simply incorrect ideas but coherent mental models that make sense within students' naïve worldviews, sustained by perceptual experiences and cognitive heuristics (Coley & Tanner, 2012; Leonard, Kalinowski, & Andrews, 2014).

Common misconceptions across biological domains

Misconceptions are ubiquitous across biological domains. In **cellular biology**, students often perceive cells as homogenous structures or equate them to miniature "bags of fluid," neglecting their compartmentalization and functional specialization (Tanner & Allen, 2005). In **genetics**, many learners mistakenly believe that genes directly "control" traits in a one-to-one correspondence, ignoring gene-environment interactions and regulatory mechanisms (Leonard et al., 2014). **Evolutionary biology** presents perhaps the most persistent conceptual difficulties—students frequently invoke teleological explanations, such as "organisms evolve traits because they need them," reflecting goal-oriented reasoning rather than population-level natural selection (Heddy & Sinatra, 2013). In **ecology**, a prevalent misconception is that energy cycles within ecosystems rather than flows and dissipates, a misunderstanding stemming from everyday experiences with recycling (Fisher & Moody, 2002). Finally, in **human physiology**, students often misattribute breathing solely to the intake of oxygen and overlook carbon dioxide exchange and cellular respiration processes (Bahar, 2003).

Cognitive and experiential sources of misconceptions

These alternative conceptions derive from **cognitive construals**—intuitive frameworks of reasoning such as *teleological*, *essentialist*, and *anthropocentric* thinking (Coley & Tanner, 2012). Teleological reasoning attributes purpose to biological phenomena ("the heart beats to keep us alive"), while essentialist thinking assumes that species possess immutable internal "essences." These mental shortcuts, while adaptive in everyday cognition, distort scientific interpretation.

Experientially, learners often overgeneralize from observable phenomena, leading to conceptual distortions. For example, observing that plants are stationary may reinforce the false idea that they are passive organisms without internal processes. Gouvea and Simon (2018) argue that such "cognitive construals" are not static misconceptions but dynamic reasoning patterns emerging from students' efforts to make sense of complexity. Because these frameworks are embedded in perceptual and linguistic habits, they resist correction through rote memorization or direct explanation.

Mechanisms of persistence despite instruction

Misconceptions persist due to the **robustness of cognitive schemas** and **fragmented conceptual change**. Traditional instruction often fails to dislodge these misconceptions because it emphasizes factual recall rather than cognitive restructuring. Learners assimilate new information into existing mental models instead of accommodating fundamentally different explanatory frameworks (diSessa, 2014). For instance, students may memorize that "natural selection causes evolution" but continue to interpret it as "organisms adapt intentionally."

Moreover, emotional and motivational factors contribute to persistence. Heddy and Sinatra (2013) found that conceptual change requires affective engagement and personal relevance; without these, students may reject conflicting information as counterintuitive.

Leonard et al. (2014) further argue that conceptual change is a *socio-cognitive process*—students' identities, worldviews, and community beliefs shape how they interpret biological explanations. Hence, misconceptions endure not merely due to cognitive inertia but through the reinforcement of epistemic beliefs and cultural narratives.

Overcoming misconceptions: Toward conceptual reconstruction

Effective remediation requires instructional strategies grounded in **conceptual change theory**, emphasizing cognitive conflict, model-based reasoning, and metacognition. Tanner and Allen (2005) advocate inquiry-based learning that confronts misconceptions through evidence and reasoning rather than correction. Similarly, Gouvea and Simon (2018) propose reframing misconceptions as "productive beginnings," recognizing that intuitive reasoning can scaffold deeper understanding when guided appropriately.

In sum, students' misconceptions in biology are sustained by deeply rooted cognitive heuristics and experiential interpretations that resist superficial instructional approaches. Overcoming them demands sustained engagement, emotional investment, and explicit scaffolding toward mechanistic and system-level reasoning.

Effective pedagogical approaches for enhancing biological concept comprehension and science literacy

Advancing students' understanding of biological concepts and their scientific literacy requires pedagogical approaches that actively engage learners in inquiry, reflection, and culturally relevant contexts. Current research underscores the efficacy of inquiry-based learning (IBL), conceptual change instruction, hands-on experimentation, and culturally responsive pedagogy in cultivating robust and transferable understanding of biological phenomena. The integration of these methods, grounded in constructivist and sociocultural learning theories, yields sustained conceptual gains and positive scientific attitudes.

Inquiry-based learning (IBL)

Inquiry-based learning remains one of the most effective strategies for enhancing conceptual understanding and scientific literacy. IBL promotes curiosity-driven exploration, hypothesis testing, and reflective reasoning—core components of scientific practice. Gomez (2025) found that students engaged in structured inquiry activities demonstrated higher retention of biological concepts and improved ability to apply knowledge to novel contexts. Similarly, Morris (2025) emphasized that inquiry models aligned with the Next Generation Science Standards (NGSS) foster not only conceptual mastery but also metacognitive and collaborative skills essential for literacy development.

Empirical evidence from Thailand and Malawi indicates that inquiry-based frameworks, particularly the 7E instructional model (engage, explore, explain, elaborate, evaluate, extend, and enrich), significantly improve students' comprehension of complex biological processes such as cellular respiration and photosynthesis (Uthaikanchanakul, 2025; Chikaluma & Opanga, 2022). Effective IBL interventions feature scaffolded questioning, authentic problem-solving, and student autonomy balanced with guided facilitation.

Conceptual change instruction and hands-on experimentation

Conceptual change pedagogy specifically targets misconceptions by promoting cognitive conflict and restructuring of prior knowledge. Nkosi (2022) demonstrated that integrating conceptual change lessons into science classrooms fosters deep learning, as students confront their intuitive beliefs and reconstruct them through evidence-based reasoning. When combined with hands-on experimentation, conceptual change becomes experiential—students not only challenge misconceptions theoretically but also observe biological phenomena directly. Experiments designed to visualize abstract processes, such as diffusion or genetic inheritance, serve as "conceptual anchors" that bridge concrete experience with abstract reasoning.

Effective hands-on instruction incorporates model-based learning, where students construct, test, and revise representations of biological systems. This iterative approach enhances cognitive coherence across domains, supporting long-term retention and scientific problem-solving.

Culturally responsive pedagogy and contextualized science learning

Culturally responsive pedagogy (CRP) emphasizes the integration of students' cultural experiences, languages, and community practices into science education. Brown (2017) and Brown and Crippen (2016) demonstrated that combining CRP with inquiry-based science enhances equity and engagement by making scientific inquiry socially relevant. Contextualized instruction—such as connecting ecological studies to local environmental issues or using indigenous knowledge in health-related topics—fosters identity affirmation and science literacy among underrepresented groups.

Babaci-Wilhite (2017) further argued that embedding inquiry within local linguistic and cultural contexts significantly improves scientific literacy, especially in multilingual settings. Instructional congruence—aligning science discourse with cultural norms—reduces cognitive dissonance and supports "border crossing" between everyday and scientific ways of knowing (Magee & Meier, 2011).

Instructional design principles

Across successful interventions, three instructional design principles consistently emerge:

1. Scaffolded Inquiry and Cognitive Challenge: Effective designs balance student autonomy with guided instruction, prompting learners to articulate and test hypotheses within structured phases.
2. Metacognitive Reflection: Encouraging students to reflect on their reasoning processes enhances conceptual change and transferability of knowledge.
3. Cultural and Contextual Relevance: Integrating local issues, cultural practices, and linguistic diversity contextualizes science, promoting inclusion and relevance.

These principles align with constructivist epistemology, wherein learners actively build meaning through dialogue, experimentation, and culturally situated inquiry.

Implications for enhancing biological concept understanding and authentic science literacy

The cultivation of authentic science literacy—defined as the ability to apply biological knowledge critically, reason scientifically, and solve real-world problems—demands systemic reform in instructional practice, curriculum design, assessment, and teacher professional development. Recent empirical studies emphasize that traditional fact-based instruction must evolve into a competency-based framework that integrates inquiry, argumentation, and socio-scientific reasoning (Suwono, Rofi'Ah, & Saefi, 2023; Jamil, Bokhari, & Rafiq, 2024).

Instructional practice: From transmission to transformation

Instructional design must prioritize active learning methodologies that foster cognitive engagement, collaboration, and critical inquiry. The Interactive Socio-Scientific Inquiry (ISSI) approach, developed by Suwono et al. (2023), demonstrates significant gains in biological knowledge and critical thinking by embedding ethical reasoning and real-world problem solving within inquiry-based contexts. Similarly, Kusuma (2023) found that integrating problem-based learning (PBL) with digital tools enhances both biological literacy and critical reasoning, enabling students to connect conceptual understanding to environmental and health-related phenomena. Pedagogically, effective instruction emphasizes metacognition, reflective dialogue, and evidence-based reasoning, guiding learners to evaluate claims and synthesize knowledge across biology domains. Teachers must act as facilitators, fostering intellectual autonomy and adaptive thinking rather than delivering static information (Hogan & O'Flaherty, 2021).

Curriculum design: Integrative and contextual frameworks

Curriculum reform should shift from content accumulation to conceptual integration and authentic context alignment. Jamil et al. (2024) argue that current biology curricula often prioritize factual memorization over higher-order cognitive engagement, limiting students' critical literacy. A re-envisioned biology curriculum must explicitly incorporate cross-cutting concepts—such as systems thinking, energy flow, and genetic mechanisms—through real-world contexts like climate change, biodiversity, and health science. Additionally, the curriculum should embed transdisciplinary learning, linking biology with mathematics, technology, and environmental ethics to reflect the complexity of biological inquiry. Suwono et al. (2023) highlight that socially contextualized inquiry enhances students' sense of scientific agency, aligning learning with sustainability and civic responsibility.

Assessment approaches: Evaluating reasoning and application

Traditional assessments emphasizing recall fail to capture students' capacity for scientific reasoning. Authentic assessment models—such as performance-based tasks, scientific argumentation portfolios, and problem-solving investigations—better evaluate conceptual understanding and application (Muhibbuddin & Yustina, 2020).

Effective assessments integrate formative feedback loops, where reflection and self-assessment guide learning progress. Sutiani (2021) demonstrated that inquiry-based assessment frameworks promote critical thinking and resilience in problem-solving, particularly when students evaluate their hypotheses against empirical evidence. Moreover, digital assessments incorporating simulations or case-based reasoning allow for authentic demonstrations of knowledge application in dynamic, real-world biological scenarios.

Teacher professional development: Building pedagogical and scientific competence

Teacher professional development (TPD) remains a cornerstone of science literacy advancement. Programs must extend beyond content knowledge to include pedagogical content knowledge (PCK), scientific reasoning, and assessment literacy (Stammen, Malone, & Irving, 2018). Workshops emphasizing modeling instruction and reflective inquiry have been shown to significantly improve teachers' reasoning and instructional design capacity in biological sciences.

Hogan and O'Flaherty (2021) advocate embedding sustainability and ethical literacy in teacher education, enabling educators to design socio-scientific learning experiences that foster environmental consciousness alongside conceptual understanding. Continuous TPD also necessitates professional learning communities that encourage peer collaboration and iterative innovation.

The future of biology education hinges on systemic transformation guided by integrative, inquiry-oriented, and socially responsive pedagogical models. Instruction must cultivate critical consciousness, curricula should connect science to societal relevance, assessments must value reasoning and creativity, and teachers must be empowered as reflective practitioners. Collectively, these reforms bridge the gap between scientific knowledge and scientific literacy, preparing learners not only to understand biology but to *think and act biologically* in addressing global challenges.

Conclusion

The collective analysis of cognitive, pedagogical, and institutional dimensions in biological education reveals that the development of authentic science literacy depends upon the dynamic interaction between learners' cognitive processes, conceptual frameworks, and instructional environments. Students' comprehension of biological concepts across domains such as cellular biology, genetics, ecology, and human physiology is mediated by hierarchical cognitive mechanisms that evolve with developmental maturity and prior knowledge. As learners progress through basic education, their cognitive capacity transitions from concrete operational thought to formal reasoning, enabling them to interpret abstract and systemic phenomena—such as genetic inheritance, ecological equilibrium, and physiological regulation—through causal and mechanistic reasoning rather than intuitive perception. However, this evolution is neither linear nor uniform; it is deeply influenced by the coherence and structure of prior knowledge, which can either scaffold or distort new understanding.

Persistent misconceptions remain a formidable barrier to conceptual mastery. Students' intuitive frameworks—rooted in teleological, essentialist, and anthropocentric thinking—generate and sustain alternative conceptions that resist correction through traditional instruction. Misunderstandings such as perceiving evolution as purposeful adaptation, energy as cyclical rather than unidirectional, or genes as discrete physical traits exemplify the enduring influence of experiential biases and cognitive shortcuts. These misconceptions persist because formal instruction often fails to provoke the cognitive dissonance required for genuine conceptual change. Instead, new information is assimilated superficially into existing mental schemas, producing fragmented and context-bound understanding. Effective remediation thus requires pedagogical designs that engage learners in epistemic conflict, reflection, and evidence-based reasoning.

Among the diverse instructional approaches examined, **inquiry-based learning (IBL)**, **conceptual change pedagogy**, **hands-on experimentation**, and **culturally responsive instruction** consistently demonstrate the greatest efficacy in fostering deep biological understanding and science literacy. These methods align with constructivist and sociocultural theories of learning, positioning students as active constructors of meaning within authentic, contextually grounded inquiry. When instruction incorporates guided questioning, argumentation, and model-based reasoning, learners develop not only content knowledge but also critical thinking, metacognitive awareness, and the ability to apply scientific reasoning to real-world challenges. Culturally responsive pedagogy further strengthens engagement and relevance by situating scientific inquiry within learners' social and cultural realities, thus bridging the divide between school science and lived experience.

The implications for educational practice are profound. Curriculum design must transcend rote factual delivery, integrating cross-cutting concepts and socio-scientific issues that cultivate higher-order cognitive engagement. Assessments should evaluate reasoning, creativity, and application through performance-based and formative models rather than static recall tests. Most crucially, teacher professional development must prioritize pedagogical content knowledge, inquiry facilitation, and reflective practice, enabling educators to function as designers of learning experiences rather than conveyors of information. In this framework, biological literacy becomes not merely the acquisition of knowledge but the cultivation of a scientifically informed worldview—one that empowers learners to think critically, reason empirically, and act ethically within an increasingly complex biological and ecological world.

Ultimately, advancing biological education demands a holistic transformation grounded in cognitive insight, pedagogical innovation, and systemic support. By aligning teaching, curriculum, and assessment with the principles of developmental learning and conceptual change, educators can nurture scientifically literate citizens capable of integrating knowledge with critical inquiry, thereby bridging the enduring gap between understanding biology and *thinking biologically* in everyday life.

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