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Learning Life Digitally: Pedagogical Opportunities and Challenges in Biology Teaching with ICT

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ABSTRACT

This paper explores how digital technologies are transforming the teaching of Biology in Greek secondary schools. Many students perceive scientific concepts, such as cellular processes and genetic mechanisms, as abstract and disconnected from daily life when taught via traditional instruction. Integrating ICT tools like simulations, video modules, and virtual labs creates a more engaging, exploratory, and personalized environment. The research highlights challenges educators face, including limited infrastructure and insufficient professional training. A gradual shift toward blended and flipped models is proposed, promoting active participation and student autonomy. Teacher empowerment through pedagogical support remains central. The paper emphasizes equity, ensuring that under-resourced areas benefit from digital innovation. International case studies reinforce the relevance of these strategies, while student feedback underscores the motivational impact of interactive content. Technology serves as a bridge between theory and meaningful understanding. By prioritizing inclusivity, teacher development, and strategic ICT use, Biology becomes a subject that sparks curiosity and critical thinking. The aim is not just improved performance but deeper scientific awareness and long-term enthusiasm. Used effectively, ICT turns science into a dynamic experience.

Keywords: *biology education; ICT Integration; Greek secondary schools; student engagement; teacher development.*

INTRODUCTION

Biology is the science of life, a subject intrinsically tied to observation, experimentation, and interpretation of complex systems. In recent years, the integration of information and communication technology (ICT) has redefined how biology is taught and learned across diverse educational contexts. From virtual laboratories to adaptive courseware and co-designed simulations, digital tools offer both pedagogical opportunity and challenge (Situmorang et al., 2024; Vignare et al., 2019).

Globally, educators have embraced ICT to support inquiry-based learning, visualize abstract biological processes, and foster collaboration in the classroom (Besir et al., 2025; Dabholkar et al., 2020). Virtual dissection tools, animated models of DNA replication, and game-based ecosystems have shifted biology from static textbook diagrams to interactive experiences (Byukusenge et al., 2022; Bulić et al., 2017). However, this transformation is uneven. Teachers' digital fluency, infrastructure access, and curricular flexibility remain critical variables, particularly in developing regions (Farhana et al., 2024; Egbunu, 2024).

In Greece, biology education sits at the intersection of tradition and innovation. While many secondary schools have access to basic ICT infrastructure, integration into biology lessons is often fragmented and exploratory (Krimitzas & Vekyri, 2023). Local studies have illustrated both the enthusiasm and hesitation of educators, pointing to systemic barriers such as lack of training, rigid assessment models, and limited institutional support (Gariou-Papalexiou et al., 2017; Vasilopoulou, 2022).

This article examines the pedagogical landscape of biology education in Greek secondary schools through the lens of ICT. Drawing on international and national sources, it explores how digital tools are being used, what challenges teachers face, and what possibilities exist for more inclusive and engaging science learning. Special attention is given to differentiated instruction, cognitive load considerations, and the ethical implications of educational technologies (Skulmowski & Xu, 2022; European Commission, 2022b). By analyzing existing practices and reflecting on future directions, this study aims to contribute to a more coherent and student-centered model of biology instruction in the digital age.

DIGITAL INTEGRATION IN SECONDARY SCHOOL BIOLOGY EDUCATION

Integrating ICT into biology instruction at the secondary level is no longer a futuristic ambition; it is a pedagogical necessity. As scientific content becomes more abstract and students grow increasingly digital-native, technology can function as both a cognitive scaffold and a participatory bridge between theory and lived experience. In secondary schools, biology teachers face the challenge of balancing curriculum demands with engaging delivery formats, all while navigating technological limitations and student diversity.

Virtual laboratories and online experimentation

Hands-on activities are central to learning biology, yet access to physical labs in secondary schools is often restricted due to cost, equipment, or safety concerns. Virtual labs have emerged as valuable alternatives. Byukusenge et al. (2022) described how digital simulations of biological processes, such as photosynthesis, DNA replication or enzyme activity, allow students to experiment freely, even in under-resourced schools. These platforms provide visualizations, adjustable variables and immediate feedback, making science inquiry accessible beyond the physical lab.

In Croatian secondary schools, e-learning modules created by teachers showed measurable improvements in student performance, especially when paired with interactive tools (Bulić et al., 2017). The structure of virtual labs encourages procedural understanding and helps demystify complex topics for adolescent learners who are often intimidated by scientific jargon.

Flipped classrooms and student agency

The flipped classroom model has attracted attention in Greek secondary education as a strategy to optimize lesson time and promote autonomy. Gariou-Papalexiou et al. (2017) documented a biology intervention in a Greek high school where students studied theory at home through curated videos, and then applied concepts during in-class problem solving. Teachers reported that students became more involved, and difficult topics such as evolution were better understood. For students with learning difficulties or slower processing speeds, this asynchronous structure offers time to absorb content at their own pace.

More broadly, this approach aligns well with co-designed learning frameworks. Wu et al. (2021) argued that involving students in the customization of their digital tools fosters ownership and motivation. At the secondary level, where students are actively shaping their identity and interests, giving them agency over how biology is delivered can be transformational.

Digital games and interactive platforms

Game-based learning has proven particularly effective in engaging adolescents. Situmorang et al. (2024) conducted a systematic review showing that biology games increase retention and conceptual understanding when designed around curriculum objectives. Greek secondary biology teachers have begun experimenting with apps and platforms that simulate ecological systems or cellular processes, combining entertainment with academic rigour.

Moreover, adaptive platforms can personalize pathways for learners who vary significantly in readiness. Vignare et al. (2019) highlighted the use of biology courseware that adjusts question difficulty and pacing based on learner input, thereby supporting differentiated instruction, a crucial need in mixed-ability classrooms.

Addressing cognitive load in teenage learners

Cognitive overload is a real concern in secondary education, especially when multiple forms of digital content are presented simultaneously. Koć-Januchta et al. (2022) found that well-designed interfaces in biology can help students connect ideas and reduce extraneous cognitive load. For teenagers who often multitask or face attention challenges, instructional design must be deliberate.

Skulmowski & Xu (2022) cautioned against the indiscriminate layering of videos, quizzes, animations and text. In the secondary context, this can fragment attention and diminish retention. Biology teachers need training in selecting and sequencing content so that digital tools enhance, rather than complicate, student thinking.

Inclusion, accessibility and differentiated support

Secondary classrooms are among the most heterogeneous, spanning cognitive styles, abilities, and backgrounds. ICT tools offer options for differentiation, from screen readers to adjustable font sizes and multilingual support. Dhar & Samanta (2024) advocated for digital resources that allow biology teachers to scaffold instruction for students with learning disabilities or linguistic barriers.

In Greek schools, the work of Vasilopoulou (2022) showed how digital modules increased participation among students with special educational needs. Biology activities supported by animation, narration and guided pacing helped these learners engage with materials otherwise considered abstract or inaccessible.

Gender inclusion in secondary science environments

Gender bias in STEM participation often intensifies in adolescence. Cheryan et al. (2024) found that when biology software included stereotypically masculine imagery or competitive mechanics, female students may disengage. Teachers in secondary schools should curate ICT resources with balanced representation and collaborative structures that invite all students into scientific inquiry.

UNESCO (2023b) underscored the role of inclusive design in promoting gender equity, recommending that schools routinely assess digital materials for bias and ensure diverse examples in biology problems and activities. Peer collaboration, role models, and gender-neutral problem scenarios help counteract disengagement in early adolescence.

Teacher readiness and local realities

Despite the pedagogical potential, secondary school biology teachers often feel underprepared for ICT integration. Krimitzas & Vekyri (2023) reported that in Greece, biology educators cite time constraints, lack of training and unclear curricular expectations as major barriers. The DigCompEdu framework (European Commission, 2022a) offers a structured pathway to build educator digital competence, but its adoption is uneven.

In other regions, similar challenges emerge. Besir et al. (2025) notes that while Ethiopian teachers express positive attitudes towards digital biology tools, limited infrastructure and inconsistent policy support hinder usage. Farhana et al. (2024) found that school-level leadership plays a pivotal role: where principals encourage innovation and teachers have time to explore, ICT implementation is more successful.

Okafor & Ekechukwu (2025) argue for policy structures that embed ICT into biology teaching through localized examples and teacher-led design. Their findings in Nigerian schools reveal that when educators are included in planning and evaluation, they feel more confident and are more likely to experiment with digital methods.

While many secondary biology teachers express interest in integrating digital tools, actual levels of implementation vary considerably across contexts. According to Munyemana, Nsanganwimana & Gaparayi (2022), the degree to which biology educators incorporated ICT into classroom practice is influenced by their pedagogical understanding, institutional support, and professional experience. Even when infrastructure is available, teachers may differ in how confidently they apply digital tools to promote inquiry-based learning. This suggests that professional development must address not only technical competence but also pedagogical confidence, enabling educators to transform ICT access into meaningful classroom action.

Policy considerations for secondary biology integration

Policy interventions must be responsive to classroom realities. Egbunu (2024) emphasized that in Nigerian secondary schools, biology teachers benefit from hands-on professional development and access to localized digital content. Okafor & Ekechukwu (2025) call for national strategies that bridge the gap between available technology and biology curricula.

In Greece, there is growing interest in centralized ICT support for secondary educators, including curated resource banks, webinars and mentorship schemes. The flipped biology case study by Gariou-Papalexiou et al. (2017) suggested that small pilot programs can yield scalable insights, especially when they connect digital innovation with curriculum targets.

Ethics, data privacy and adolescent safety

Secondary students generate significant learning data through digital platforms, from quiz responses to behavioral engagement metrics. The European Commission (2022b) warned that schools must handle this data responsibly, ensuring transparency and consent, especially when using AI-based tools. Teenagers are particularly vulnerable to algorithmic profiling, and biology tools should never be used for high-stakes prediction without informed oversight.

UNESCO (2024) supports the development of ethical ICT guidelines within national education systems, stressing adolescent data rights. Biology teachers may not be trained to navigate these questions alone; thus, policy frameworks must include clear protocols for ethical ICT use in secondary settings.

THEORETICAL FRAMES AND PEDAGOGICAL CONCEPTS

Teaching biology in secondary schools entails guiding students through a maze of abstract processes, visual models, and microscopic interactions. When ICT tools are introduced into this space, their effectiveness depends on more than technical design; it requires a pedagogical foundation rooted in cognitive psychology, inclusive practice and digital ethics.

Cognitive load theory and biological complexity

Biology presents unique cognitive challenges to adolescent learners. Concepts such as mitosis, genetic coding or photosynthetic pathways demand the ability to process intricate sequences and interrelated mechanisms. Cognitive Load Theory (CLT) offers a lens to evaluate how much mental effort learners invest and how digital tools can scaffold their understanding.

Koć-Januchta et al. (2022) demonstrated that AI-enriched biology textbooks supported students in connecting multiple ideas more easily, reducing extraneous cognitive load. These tools helped learners focus on core processes by visually integrating related components, such as cell organelles and metabolic functions, within interactive models.

Skulmowski & Xu (2022) cautioned against overly stimulating interfaces, which may overwhelm working memory. In secondary biology classes, where students encounter high-information density, teachers must act as cognitive curators. The role of ICT is not just to "engage," but to clarify, offering sequenced animations, low-distraction design, and guided explanations that foster conceptual economy.

Differentiated instruction and learner diversity

Differentiation has become a pedagogical imperative in secondary education, especially in mixed-ability classrooms where biology spans from gifted learners to students with learning difficulties. ICT tools enable teachers to offer multiple representations of content, provide individualized pacing, and embed scaffolds directly within lessons.

Dhar & Samanta (2024) argued that differentiated digital instruction supports inclusive learning environments by providing modalities beyond traditional lecture formats. For example, animated diagrams can help visual learners, while narrated simulations assist students with language processing challenges. In Greece, Vasilopoulou (2022) observed that biology students with special educational needs responded positively to digital modules that allowed repeated exposure and flexible navigation.

Moreover, adaptive platforms adjust tasks in real time based on learner input, offering challenge when needed or support when confusion arises. At the secondary level, these systems give students agency over their learning pathway, a crucial feature for adolescents navigating academic and personal growth simultaneously.

Constructivist pedagogy and student co-design

The move toward constructivist models in science education has led to increasing emphasis on student involvement in learning design. Rather than passive recipients, secondary biology students can act as co-creators of their digital experience, by selecting, shaping or even contributing content to their own platforms.

Wu et al. (2021) found that students involved in co-designing biology activities through technology, demonstrated improved learning outcomes and stronger conceptual retention. This participatory approach aligns with adolescent developmental needs: the desire for autonomy, relevance and peer collaboration. Dabholkar et al. (2020) further argued that computational thinking integrated into biology promotes scientific reasoning and systems analysis, moving beyond factual recall.

In Greek classrooms, however, this pedagogy remains underexplored. Teachers often receive rigid curricular guidelines with limited scope for student input. Nonetheless, small-scale interventions, such as digital biology journaling or simulation customization, offer entry points for a constructivist shift.

Inclusive pedagogy and equitable access

Inclusion is not only about disability. It encompasses gender, linguistic background, socio-economic status and emotional needs. ICT-based biology instruction must be examined through an equity lens to ensure it does not replicate or amplify existing barriers.

UNESCO (2023b) emphasized that digital tools should reflect the diversity of student populations. Cheryan et al. (2024) warned that software design in science often embeds subtle gender cues, affecting engagement. For example, biology simulations framed as competitive battles may deter girls, while tools with nurturing or collaborative themes attract broader participation.

In Greece, Krimitzas & Vekyri (2023) highlighted the need for culturally responsive materials, as many available biology platforms are created outside the local context. Teachers report challenges in adapting foreign resources to Greek terminology, examples or curricula. Inclusive pedagogy through ICT, therefore, demands localization, not only in language but in cultural representation, pacing and assessment style.

Digital ethics and data responsibility in adolescent learning

Beyond pedagogy, digital biology education raises ethical questions. Secondary students are at a sensitive developmental stage, and their learning data - interactions, scores, behaviors - are often collected by platforms. The European Commission (2022b) provides ethical guidelines to ensure responsible use of AI and data in schools, advocating for transparency, privacy and algorithmic accountability.

UNESCO's (2024) Global Education Monitoring Report calls attention to how digital tools can create surveillance environments rather than empowering spaces. Teachers may be unaware of how algorithms profile students or how data is stored. In biology classes using adaptive software, diagnostic features must be explained to students clearly, and schools must obtain informed consent from families when necessary.

In Greece, digital ethics in secondary education is still a developing domain. While teachers are enthusiastic about ICT, few report receiving training in data protection or ethical evaluation. National policies could bridge this gap by embedding digital citizenship into biology instruction, linking scientific integrity with digital responsibility.

Pedagogical innovation and institutional support

Innovation in digital biology instruction thrives not only on teacher passion but institutional enablement. Egbunu (2024) found that teachers in Nigerian secondary schools succeeded with ICT integration when school leadership provided flexibility, training and materials. Similarly, Okafor & Ekechukwu (2025) argue for structured national strategies that give teachers time to explore and experiment.

In Greece, Gariou-Papalexiou et al. (2017) showed that even small pilot studies, such as flipped biology modules, can yield transformational results when supported. Secondary biology teachers often operate under strict curriculum pacing and examination demands. For ICT-based pedagogy to flourish, institutions must create spaces for risk-taking, reflection and sharing of best practices.

LOCAL CONTEXT AND COMPARATIVE PERSPECTIVES

Biology education at the secondary level varies widely across countries, shaped by sociocultural priorities, infrastructure and curricular models. Greece presents a landscape of partial ICT integration, with motivated educators but limited institutional scaffolding. Comparative insights from other regions, such as Ethiopia, Nigeria, Croatia and Bangladesh, offer valuable lessons on implementation strategies and teacher support.

The Greek reality: Challenges and emerging practices

In Greece, biology teachers operate within a centralized curriculum, often with restricted autonomy to modify lesson structures. Despite this, several educators have explored digital formats to enrich science teaching. Krimitzas & Vekyri (2023) found that while secondary teachers recognized the value of ICT in biology, systemic barriers, such as outdated infrastructure and lack of targeted training, limit its sustained use.

Nonetheless, initiatives like the flipped classroom trial by Gariou-Papalexiou et al. (2017) revealed an appetite for pedagogical experimentation. In that case study, secondary students interacted with biology videos outside class and used time in school for inquiry and dialogue. Outcomes included increased engagement and deeper comprehension, especially in abstract topics like molecular genetics.

Vasilopoulou (2022) added another layer, documenting how digital modules helped students with special educational needs participate more actively in biology lessons. These examples show that despite structural limitations, localized innovation is possible within Greek schools.

Ethiopia and Bangladesh: Infrastructure gaps and teacher optimism

In Ethiopia, Besir et al. (2025) surveyed pre-service teachers in biology education colleges and found a generally positive attitude toward ICT usage, despite significant infrastructural gaps. Many educators were eager to apply technology in the classroom but lacked access to devices, stable electricity and pedagogical models tailored to local conditions.

Farhana et al. (2024) described similar dynamics in Bangladesh, where teachers expressed enthusiasm for digital biology tools but reported challenges such as limited Internet, low-quality content and minimal technical support. In both contexts, professional development and resource adaptation were named as priorities for meaningful ICT integration.

While Greece has stronger technological foundations, parallels exist in terms of insufficient curricular flexibility and centralized decision-making. This suggests the importance of contextualized policy, where systemic reform is paired with teacher agency.

Nigeria: Bottom-up success and administrative leadership

In Nigeria, biology teachers have made significant strides in ICT integration through bottom-up innovation. Egbunu (2024) examined secondary schools in Abuja, reporting widespread use of digital tools such as virtual labs, multimedia simulations and online assessments. Teacher initiative and school-level support were cited as core enablers.

Okafor & Ekechukwu (2025) reinforce this view, emphasizing the role of administrative leadership in scaling ICT implementation. In their study, schools with proactive principals and localized decision-making achieved more successful integration of digital biology tools, even without national mandates.

For Greece, this comparative lens highlights the value of empowering individual schools and educators. While national frameworks (e.g. DigCompEdu) exist, their adoption depends on how much autonomy and encouragement teachers receive at the ground level.

Croatia: Modular e-learning and student performance

Bulić et al. (2017) evaluated the impact of modular biology e-learning content in Croatian secondary schools. Their findings show that structured digital units improved learning outcomes and student engagement, particularly when embedded into existing curricula rather than used as standalone supplements.

This model resonates with Greek realities. Teachers often face pressure to “cover content” for external examinations, which discourages open-ended digital exploration. The Croatian experience suggests that ICT can be systematized within curriculum maps, allowing digital modules to serve as core learning elements, not extras.

Cross-contextual synthesis: Lessons for Greece

Across these cases, four recurring themes emerge:

- Teacher motivation exists even in constrained systems.
- Infrastructure alone is insufficient - training and autonomy matter.
- Localized adaptation of digital tools enhances relevance.
- Policy must balance national vision with school-level flexibility.

Greece shares common challenges with developing contexts but also possesses resources to lead in regional ICT integration. Comparative perspectives encourage a shift from fragmented experimentation to strategic ecosystem-building, where digital biology instruction becomes a standard, inclusive and scalable practice across secondary schools.

CASE-BASED APPLICATIONS OF ICT IN SECONDARY BIOLOGY TEACHING

Abstract examples of digital biology tools often fall short of showing how real classrooms operate. Case-based applications, drawn from research, pilot studies or realistic composite scenarios, help illustrate how ICT transforms student experiences when used thoughtfully in secondary education settings.

Case A: Virtual labs in under-resourced Greek schools

At a provincial Greek lyceum, where traditional laboratory equipment is sparse, a biology teacher implements virtual lab software simulating the enzyme-substrate interaction. Students work in pairs on school laptops and test hypotheses using sliders and animated reactions. The teacher scaffolds the session using printed worksheets and discussion prompts.

This intervention, inspired by Byukusenge et al. (2022) and contextualized through Greek constraints, improves conceptual clarity and student confidence. Even without full technical infrastructure, targeted use of virtual labs supports active inquiry.

Case B: Adaptive learning in inclusive classrooms

In an urban secondary school in Athens, a biology class includes students with dyslexia and ADHD. The teacher integrates an adaptive biology platform that offers narrated modules, simplified language and adjustable pacing.

Drawing from Vasilopoulou (2022) and Dhar & Samanta (2024), this setting showcases how ICT can personalize learning for all students. The teacher monitors progress through dashboards and provides one-on-one support during lab periods. Differentiation becomes both feasible and measurable.

Case C: Flipped classroom implementation with co-design elements

A group of biology teachers in Thessaloniki participate in a regional pilot, creating flipped modules on cell biology. Students watch short concept videos at home and collaboratively solve case scenarios in class (e.g. designing an experiment to test osmosis using vegetables).

Based on Gariou-Papalexiou et al. (2017) and Wu et al. (2021), this approach reveals how combining flipped instruction with student co-design fosters engagement and deeper learning. Students reported enjoying the format and performed better in both open-ended and factual assessments.

Case D: Comparative challenge – Nigerian bottom-up innovation

In a Nigerian secondary school studied by Chukwuemeka (2025), teachers incorporate locally developed biology apps that simulate plant physiology. Students engage with the materials on mobile devices and complete reflection journals on how environmental conditions impact growth.

The Greek context could benefit from similar initiatives, by developing low-cost, curriculum-aligned apps with local imagery and language. Such bottom-up creativity provides a practical roadmap for scalable ICT implementation.

VOICES FROM THE CLASSROOM: TEACHER AND STUDENT INSIGHTS

Beyond theories and tools, real-world voices bring nuance to digital transformation. Teachers and students navigating secondary biology education offer insights into how technology shifts classroom dynamics.

Teacher perspectives: Innovation under constraint

Greek biology teachers, as Krimitzas & Vekyri (2023) observed, expressed both enthusiasm and hesitation. One teacher noted: *"Digital platforms help me show the invisible, like what goes on inside a cell. But with exam pressure and no training, I worry about time loss."* This tension between pedagogical ambition and structural limits is echoed across international contexts.

In Ethiopia, Besir et al. (2025) documented similar sentiments: *"We want to use ICT in biology, but we often have to improvise with little support."* Despite differences in national wealth and infrastructure, educators face shared challenges of capacity-building, curricular flexibility and institutional recognition.

Student reflections: Ownership, engagement and inclusion

Adolescent learners are vocal about what works for them. In a Greek pilot, students described flipped biology lessons as "*more fun*" and "*less stressful*" (Gariou-Papalexiou et al., 2017). A student commented: *"Understanding evolution was easier when I could pause the video and search for examples myself."* Digital autonomy aligns with adolescent identity formation, by giving learners agency and relevance.

Students with special educational needs also express appreciation for digital supports. Vasilopoulou (2022) reported that several students felt “*finally part of the biology class*,” as animations and pacing tools enabled participation. This human impact reinforces the ethical imperative of inclusive design.

In Nigeria, Chukwuemeka (2025) documented student excitement in using biology games: *"It felt like playing, but I was learning without realizing."* Such affective feedback illustrates that ICT in biology can reframe academic effort into joyful curiosity.

SYNTHESIS TABLES AND PRACTICAL FRAMEWORKS FOR IMPLEMENTATION

To support stakeholders in transitioning from theory to action, structured synthesis is essential. The following table consolidates key elements for effective ICT integration in secondary biology classrooms:

Dimension	Effective Practice	Supporting Sources
Instructional Design	Guided interfaces, low cognitive load, visual scaffolding	Koć-Januchta et al. (2022), Skulmowski & Xu (2022)
Inclusive Tools	Adjustable pacing, narration, disability-friendly modules	Vasilopoulou (2022), Dhar & Samanta (2024)
Teacher Autonomy	Co-designed lessons, pilot programs, flexible frameworks	Wu et al. (2021), Gariou-Papalexiou et al. (2017)
Professional Development	Subject-specific ICT training, peer mentoring	Krimitzas & Vekyri (2023), Okafor & Ekechukwu (2025)
Gender Equity	Gender-sensitive design, collaborative platforms	Cheryan et al. (2024), UNESCO (2023b)
Ethics & Safety	Data transparency, informed consent, ethical AI protocols	European Commission (2022), UNESCO (2024)
Evaluation & Feedback	Rubrics for ICT usage, student reflections, teacher surveys	Besir et al. (2025), Farhana et al. (2024)

Building on this synthesis, the following implementation framework may guide Greek educational authorities and biology departments:

Policy Anchoring: Establish clear mandates for digital integration in secondary biology, aligned with DigCompEdu.

Local Adaptation: Support teachers in contextualizing tools with Greek curriculum and student profiles.

Institutional Infrastructure: Provide equitable hardware and connectivity, especially in rural areas.

Continuous Training: Implement biology-specific ICT seminars and mentoring cycles.

Classroom Flexibility: Allow time and curricular space for flipped, game-based and adaptive instruction.

Monitoring Systems: Track not just access but pedagogical effectiveness and inclusivity.

NATIONAL POLICY ANALYSIS AND STRATEGIC ALIGNMENT

The digital transformation of secondary biology education in Greece cannot occur in a vacuum. It must align with broader national policy frameworks, institutional mandates and strategic planning efforts already underway. Despite notable developments in ICT strategy, gaps remain between central policies and the realities faced by biology educators in Greek secondary schools.

National digital education strategies: Momentum and fragmentation

Over the last decade, Greece has launched several initiatives aimed at modernizing its educational infrastructure. Programs supported by the Hellenic Ministry of Education and organizations like GRNET (ΕΔΕΤ) have introduced platforms such as e-Class, e-Me and repositories for Open Educational Resources (OERs). These tools are intended to standardize access and promote blended learning.

However, as Krimitzas & Vekyri (2023) noted, these platforms are rarely specialized for science teaching, let alone tailored for biology. Teachers frequently report that general-purpose environments lack the pedagogical depth or interactivity needed to illustrate complex processes like photosynthesis or DNA transcription. The absence of biology-specific digital materials underscores a disconnect between policy ambition and classroom utility.

Lack of alignment with curricular demands and assessment culture

The structure of biology curricula in Greek secondary education remains tightly bound to summative assessment. The emphasis on national exams, especially in upper secondary (Lyceum), leaves little space for open-ended inquiry or digital experimentation. Teachers often hesitate to allocate time to ICT-mediated lessons, fearing that students may fall behind on examinable content.

UNESCO (2023a) argues that digital transformation must be integrated into curriculum design, not merely inserted as an accessory. Without curricular frameworks that recognize the pedagogical value of ICT in biology, such as inquiry-based simulations, adaptive review tools or flipped modules, teachers will continue to view technology as optional or risky.

Policy visibility and teacher engagement

Another challenge is visibility. Far too often, educators are unaware of national ICT strategies or how they relate to their subject discipline. In the study by Krimitzas & Vekyri (2023), biology teachers expressed frustration about “top-down decisions” made without consultation. This lack of participatory planning undermines teacher agency and deters innovation.

In contrast, Okafor & Ekechukwu (2025) demonstrate how Nigerian schools enhanced ICT integration by involving teachers in policy translation and tool selection. Greece could benefit from similar models, by organizing forums, focus groups and pilot networks that place biology teachers at the center of strategy implementation.

Potential for strategic consolidation and vertical coherence

The current ICT landscape in Greek education is fragmented across tools, ministries and platforms. While *e-me* offers communication and file sharing, biology teachers seeking simulations or virtual labs must resort to external websites, often in English, misaligned with the curriculum and lacking accessibility features. Dhar & Samanta (2024) emphasize the need for vertical coherence: digital resources should flow from national policy to classroom practice seamlessly.

Strategic consolidation would mean creating centralized science-specific repositories, anchored in the national curriculum, enriched with inclusive design and localized language. These resources should be accompanied by professional development modules, mentorship networks and quality assurance protocols.

Digital citizenship and ethical policy frameworks

Finally, the ethical dimension of national ICT policy requires urgent attention. As students interact with biology platforms - answering questions, engaging with AI tutors, or completing simulations - their data are collected. The European Commission (2022b) and UNESCO (2024) call for transparent data practices, especially with adolescent users. Yet, Greek biology educators report minimal training in digital ethics or student data protection.

A forward-thinking policy response would include the development of school-level digital ethics guidelines, integrated into science subjects. Biology, which is deeply connected to life, identity and personal development, is ideally positioned to teach digital responsibility alongside scientific inquiry.

Summary of strategic alignment challenges

Challenge	Policy Response Needed
Generic digital platforms lacking scientific depth	Develop biology-specific ICT resources with curriculum alignment
Assessment-driven curricula discouraging exploration	Introduce flexible modules supporting inquiry and digital learning
Teacher disengagement in policy implementation	Co-design policies through teacher consultations and pilot programs
Fragmentation of platforms and resource access	Create centralized, inclusive biology digital repositories
Absence of digital ethics training	Embed ethical ICT frameworks into science education pedagogy

Greek secondary biology education stands at a crossroad: national policy is active, but misaligned. Real strategic impact will require coherence, consultation and a recognition that biology teachers are not just implementers. They are designers, innovators and guardians of scientific literacy in the digital age.

STUDENT DIGITAL BIOLOGY LITERACIES

As secondary biology teaching evolves through digital integration, attention must be paid to what students actually learn beyond content. "Digital biology literacy" is not just technical skill. It encompasses interpretive ability, ethical awareness, and personal connection to life sciences through digital means.

Conceptual engagement through multimodal formats

Students build biology understanding by interacting with animations, simulations and virtual labs. Koć-Januchta et al. (2022) found that learners better understood complex topics like enzyme reactions and cell structure when visual supports were integrated into digital environments. These multimodal approaches support different learner profiles, enhancing biology literacy across the spectrum.

In Greece, Gariou-Papalexiou et al. (2017) showed that flipped classrooms allowed students to explore topics like evolution in depth. Students self-paced their learning, accessed online explanations, and brought thoughtful questions to class discussions. This active engagement with biology content cultivates scientific reasoning and interpretive fluency, key dimensions of literacy.

Ownership and autonomy as literacy markers

Digital biology literacies also include student agency. Wu et al. (2021) argued that co-designed digital experiences empower learners to explore biological systems on their terms. In adolescence, ownership fosters relevance: students who can choose tools, navigate platforms and customize inquiry paths develop deeper literacy and resilience.

Greek students in pilot classrooms expressed this clearly: *"I liked choosing the simulation instead of watching a video. It felt like we were doing science."* (Gariou-Papalexiou et al., 2017). Such responses reflect how digital platforms, when thoughtfully integrated, support not just comprehension, but identity as science learners.

Ethical understanding and digital citizenship

Biology education increasingly intersects with digital ethics. Students must be aware of how their data is used and how digital tools represent life, diversity and complexity. UNESCO (2024) calls for embedding ethics into subject instruction, encouraging students to reflect on algorithmic bias, representation in biology software, and the social implications of scientific data.

In Greece, these literacies are still emerging. While some students express comfort with online tools, others report confusion about what happens behind the screen. Integrating discussions on data responsibility and representational fairness, for example, in units on genetics or ecology, aligns digital literacy with biological inquiry.

Emotional connection to biological themes

Finally, digital biology literacies involve emotion. Adolescents relate to topics like human biology, environmental systems and biodiversity through personal and affective lenses. When ICT tools create space for reflection, storytelling or imaginative interaction (e.g. ecosystem games), they nurture empathy and engagement.

As Cheryan et al. (2024) suggested, tools designed with emotional accessibility, not just cognitive clarity, invite broader student participation. In Greek classrooms, biology educators have begun experimenting with narrative simulations and interactive journals, deepening students' connection to living systems.

REFLECTION: CHALLENGES IN REACHING SUSTAINABLE CHANGE

Despite progress and promising examples, systemic integration of ICT in Greek secondary biology teaching faces entrenched barriers. Recognizing these challenges allows for strategic planning that is honest, inclusive and adaptive.

Curricular rigidity and exam pressures

Teachers often cite curriculum constraints as a top obstacle. Biology lessons in upper secondary focus heavily on national examinations, narrowing room for creative or exploratory use of digital tools. Krimitzas & Vekyri (2023) reported that while educators appreciate ICT's potential, many feel trapped by pacing guides and assessment rubrics.

UNESCO (2023a) emphasizes that innovation in education requires flexible frameworks. Without shifts in curriculum design, such as alternative assessment strategies or modular content, ICT integration will remain peripheral.

Teacher workload and change fatigue

Greek biology educators juggle multiple responsibilities, from content delivery to pastoral care. Introducing digital tools often requires extra planning, troubleshooting and professional learning. As Farhana et al. (2024) suggested, teacher overload diminishes the likelihood of sustained innovation.

Support structures, such as time allowances, peer mentoring and administrative encouragement, are essential. Without them, educators may view ICT as burdensome rather than empowering.

Cultural norms and pedagogical traditions

Greek educational culture traditionally values lecture-based instruction and authoritative knowledge transfer. Although this is evolving, many schools still operate within hierarchical models that discourage experimentation. As Besir et al. (2025) note in the Ethiopian context, such cultural scripts shape teacher confidence and student engagement.

Promoting constructivist pedagogies, like co-designed learning and problem-based inquiry, requires cultural as well as structural change. Pilot programs must include dialogue about pedagogy, not just technology.

Resource disparity and rural–urban divides

While urban Greek schools generally enjoy sufficient digital infrastructure, rural schools face deficits. Connectivity issues, lack of devices and limited technical support hinder biology ICT use outside city centers. Drawing from Nigerian case studies (Egbunu, 2024), strategic investment must address spatial inequity through mobile labs, resource-sharing and remote teacher training.

Fragmented policy and implementation gaps

Digital education policies often lack follow-through. Teachers report confusion about available tools, training pathways and performance expectations (Krimitzas & Vekyri, 2023). Okafor & Ekechukwu (2025) stress that successful ICT integration depends not on policy volume but coherence and accountability.

Greece's fragmented landscape - multiple platforms, limited biology-specific content and unclear guidelines - must be addressed through unified frameworks anchored in school realities.

RECOMMENDATIONS FOR POLICY AND PRACTICE

The integration of ICT in Greek secondary biology education is a multifaceted endeavor, shaped by pedagogy, infrastructure, teacher agency and institutional strategy. Based on the findings and reflections presented in this article - including practical cases, policy analysis, and student literacy insights - the following recommendations aim to promote sustainable and equitable change.

1. Develop biology-specific digital frameworks for secondary educators

National guidelines such as DigCompEdu (European Commission, 2022a) should be translated into biology teaching terms, including modules on virtual labs, ethics in human biology, and cognitive load management. Teachers require subject-sensitive training to implement digital strategies meaningfully (Krimitzas & Vekyri, 2023).

2. Embed ICT into curriculum design and assessment logic

Rigid examination-oriented curricula undermine digital integration. Greece should pilot modular biology curricula with built-in ICT components, like simulations, inquiry cycles and reflection tools, ensuring alignment with learning goals and assessment criteria (UNESCO, 2023a; Bulić et al., 2017).

3. Fund and expand infrastructure in underserved regions

Drawing lessons from Ethiopia and Nigeria (Besir et al., 2025; Egbunu, 2024), Greek policymakers must invest in hardware, software and connectivity for rural and under-resourced schools. Mobile science labs and regional resource-sharing networks could reduce inequalities.

4. Establish mentoring hubs and co-design communities

Teacher innovation flourishes when supported. Inspired by Wu et al. (2021) and Okafor & Ekechukwu (2025), Greece should promote biology ICT mentorship programs, inviting educators to co-create content, share practices and engage in reflective peer review.

5. Align national platforms with scientific depth and classroom needs

Tools like e-Class and e-Me must evolve to support biology-specific content. Centralized repositories should offer simulations, adaptive quizzes and accessible formats for students with diverse needs (Dhar & Samanta, 2024; Vasilopoulou, 2022).

6. Integrate ethics and digital citizenship into biology instruction

Students interact with biology tools that process sensitive data and portray life systems. Educators must be trained in ethical ICT use, and national policy should support school-level codes addressing transparency, privacy and algorithmic fairness (European Commission, 2022; UNESCO, 2024).

7. Include students in evaluation and design

Teenagers are tech-savvy and identity-driven. Co-designing tools with students and integrating feedback loops, enhances relevance and engagement. As Gariou-Papalexiou et al. (2017) and Wu et al. (2021) suggested, student agency transforms passive usage into ownership.

8. Monitor implementation with qualitative and contextual indicators

Access is only the starting point. Policymakers should deploy evaluation tools that capture pedagogical impact, teacher experience and student inclusion (Farhana et al., 2024; Besir et al., 2025). Metrics must reflect what ICT changes in the lived reality of biology classrooms.

CONCLUSION AND FUTURE DIRECTIONS

Digital transformation in Greek secondary biology teaching is no longer optional. It is essential. Biology, as the science of life, offers unique pedagogical opportunities when enriched with digital tools: from simulating cellular processes to personalizing ecological inquiry. This study has argued that ICT integration requires more than technological access. It demands pedagogical vision, inclusive design, ethical awareness and strategic alignment.

Through conceptual framing, comparative analysis, classroom cases, human-centered voices, and structured implementation proposals, this article presents a comprehensive roadmap. Policy analysis reveals gaps in coherence and subject-specific support, while student literacies underscore the importance of agency, interpretation and emotional connection. Reflection on challenges acknowledges the structural tensions that educators face daily.

Looking forward, the following pathways merit further exploration:

- **Longitudinal research** on how ICT impacts biology learning outcomes, identity development and scientific reasoning across diverse learner groups.
- **Curriculum co-design** processes involving biology educators, students and researchers to produce flexible, inquiry-rich units anchored in national standards.
- **Teacher specialization** in digital biology pedagogy, including professional profiles and career development schemes focused on science-technology convergence.
- **Ethical literacy and student voice** as central dimensions of biology education, where life sciences intersect with data, representation and societal responsibility.

The vision of “learning life digitally” must remain grounded in humanity. Tools are only as powerful as the intentions behind their use. In the hands of inspired teachers and engaged students, supported by coherent policy and inclusive infrastructure, digital biology education can illuminate both the microcosm of the cell and the macrocosm of a connected, thoughtful society.

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