

 Research Article

Digital Technologies in Biology Education: Opportunities and Challenges in Tunisian Schools

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Abstract

This study explores the integration of digital technologies into biology education in Tunisian secondary schools, with particular attention to their pedagogical opportunities, uses, and implementation challenges. Although educational digitalization has become an increasing priority in educational reform, significant disparities remain in infrastructure, teacher training, technological resources, and access to digital equipment, particularly in developing educational contexts. The study investigates how biology teachers integrate digital technologies into their teaching practices, the main barriers they encounter, and the pedagogical benefits they perceive. A qualitative research design was adopted, combining semi-structured interviews, classroom observations, and document analysis conducted in several Tunisian secondary schools. The participants comprised 18 biology teachers with diverse professional experiences and working in different institutional contexts. Data were analyzed thematically to identify recurrent patterns related to digital teaching practices, technological adaptation, perceived benefits, and educational constraints. The findings indicate that digital technologies can enhance student engagement and participation, facilitate the visualization and understanding of complex biological processes, and promote more interactive and learner-centered forms of teaching. They also provide teachers and students with broader access to scientific resources and support collaborative learning, inquiry-based approaches, and the diversification of instructional strategies. However, the integration of digital technologies remains constrained by inadequate technological infrastructure, limited opportunities for continuous professional development, unstable internet connectivity, unequal access to digital equipment, and insufficient institutional support. The study concludes that sustainable and effective digital integration requires not only adequate technological resources but also continuous teacher training, stronger institutional support, and educational policies adapted to local conditions. These findings highlight the importance of addressing contextual inequalities in order to promote meaningful and equitable digital transformation in biology education in Tunisia.

Keywords: Biology Education, Digital Technologies, Inquiry-Based Learning, Science Education, Secondary Schools, Tunisia

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1. INTRODUCTION

Digital technologies have become increasingly central to contemporary educational systems and are profoundly transforming teaching and learning practices worldwide. In science education, and particularly in biology education, the integration of digital tools such as virtual laboratories, simulations, online platforms, and augmented reality environments has created new opportunities for improving students' engagement, conceptual understanding, and scientific inquiry skills (Bond et al., 2021; Ibáñez & Delgado-Kloos, 2018). At the same time, the rapid expansion of educational digitalization has also generated important pedagogical, institutional, and socio-economic challenges related to technological infrastructure, teacher training, educational inequalities, and contextual adaptation (Selwyn, 2022; OECD, 2023). In Tunisia, although educational reforms increasingly encourage the integration of ICT into secondary

education, important disparities continue to affect the implementation of digital practices across schools and regions. In this context, examining the opportunities and challenges associated with digital technologies in biology education appears particularly relevant for understanding broader processes of educational transformation and pedagogical innovation within the Tunisian educational system.

1.1. Digital Transformation and the Evolution of Biology Education

Over the past decade, digital transformation has profoundly reshaped educational systems worldwide, particularly in science education. The rapid development of information and communication technologies (ICT), online learning environments, virtual laboratories, educational platforms, simulations, artificial intelligence applications, and augmented reality tools has significantly transformed teaching practices and students' learning experiences (Bond et al., 2021; OECD, 2023). Recent studies emphasize that digital technologies are no longer considered supplementary pedagogical tools but rather central components of contemporary educational ecosystems (Redecker, 2020). Biology education is especially concerned by these transformations because many biological concepts are abstract, microscopic, dynamic, and difficult to visualize through traditional teaching methods alone. Concepts related to genetics, cellular biology, ecological systems, molecular interactions, and physiological mechanisms often require visual and interactive representations to facilitate conceptual understanding and scientific reasoning. In this context, digital technologies provide important opportunities for improving visualization, experimentation, inquiry-based learning, and collaborative learning processes. Recent research demonstrates that virtual simulations, augmented reality applications, and game-based learning environments positively influence students' motivation, engagement, conceptual understanding, and higher-order thinking skills in science and biology education (Ibáñez & Delgado-Kloos, 2018; Sailer & Homner, 2020). Digital technologies may also support more active and student-centered pedagogical approaches by enabling learners to manipulate virtual scientific models and participate in interactive learning experiences.

The COVID-19 pandemic further accelerated the global integration of digital technologies into education. School closures and emergency remote teaching highlighted both the importance of digital learning environments and the structural inequalities affecting access to educational technologies (Bond et al., 2021; Dhawan, 2020). Consequently, educational digitalization has become a major concern for researchers, policymakers, and educational institutions seeking to develop more flexible, inclusive, and resilient educational systems. However, the educational impact of digital technologies remains highly dependent on contextual conditions. Research indicates that the effectiveness of digital integration depends not only on technological availability but also on teachers' professional competencies, pedagogical adaptation, institutional support, and socio-economic conditions (Selwyn, 2022; Tondeur et al., 2021). Digital transformation in education should therefore be understood not as a purely technical modernization process but as a complex pedagogical and social transformation shaped by institutional realities and educational inequalities.

1.2. Challenges of Digital Integration in Biology Education

Although digital technologies offer important pedagogical opportunities, their integration into biology education also raises multiple challenges. International studies reveal that teachers frequently encounter difficulties related to insufficient professional training, limited technological infrastructure, unstable internet connectivity, inadequate institutional support, and unequal access to digital devices among students (OECD, 2023; Trust & Whalen, 2021; Vejvoda et al., 2023). These constraints may significantly limit the effective pedagogical use of educational technologies in science classrooms. In biology education specifically, teachers must simultaneously manage scientific content complexity and technological integration. The successful implementation of virtual laboratories, digital simulations, augmented reality applications, or online collaborative platforms requires not only technical abilities but also pedagogical competencies capable of fostering inquiry-based and student-centered learning approaches. According to Mishra and Koehler (2006), effective technology integration depends on teachers' capacity to combine technological knowledge, pedagogical knowledge, and disciplinary knowledge within coherent teaching practices.

Furthermore, several scholars criticize technologically deterministic approaches that present digitalization as an automatic solution to educational problems. Digital technologies do not inherently improve learning outcomes if they are disconnected from meaningful pedagogical practices and contextual adaptation (Selwyn, 2022). Some studies also warn that excessive dependence on technology may reduce social interaction, reinforce passive learning practices, or reproduce existing educational inequalities between schools and socio-economic groups (Williamson et al., 2020). These challenges are particularly significant in Global South contexts, where educational institutions often face infrastructural limitations, unequal internet access, insufficient funding, and disparities in teacher training opportunities (Trucano, 2016). In many developing countries, digital transformation processes are strongly influenced by broader socio-economic and institutional constraints that shape schools' capacities to integrate educational technologies effectively. In Tunisia, educational reforms have progressively encouraged the integration of ICT into teaching and learning practices. However, the implementation of these reforms remains uneven across schools and regions due to disparities in technological infrastructure, internet accessibility, teacher preparation, and institutional support. These contextual realities make Tunisia an important case for examining the opportunities and limitations associated with digital integration in biology education. Consequently, teachers' adaptation strategies are essential for equitable digital education.

1.3. Research Gap and Context of the Tunisian Educational System

Despite the growing international literature on digital technologies in science education, empirical studies focusing specifically on biology education within the Tunisian secondary school context remain relatively limited. Most existing research has been conducted in technologically advanced educational systems located in Europe, North America, or East Asia, whereas considerably less attention has been devoted to North African and Global South contexts characterized by distinct institutional realities, socio-economic conditions, educational inequalities, and infrastructural constraints (Trucano, 2016). Consequently, many international studies tend to present models of digital integration that may not fully correspond to the realities of educational systems facing limited resources, unequal technological access, and structural disparities. In recent years, digital transformation has become an important component of educational reforms in Tunisia. National educational policies increasingly encourage the integration of ICT into teaching and learning practices through the development of digital platforms, online educational resources, distance learning initiatives, and technological modernization programs. These reforms are part of broader international dynamics promoting educational digitalization as a means of improving educational quality, innovation, and access to knowledge (OECD, 2023). However, despite these institutional efforts, the implementation of digital education policies remains uneven and fragmented across Tunisian secondary schools.

The Tunisian educational system therefore constitutes a particularly relevant context for examining how teachers negotiate the opportunities and challenges associated with digital technologies in biology education. Significant disparities persist between urban and rural schools in terms of technological infrastructure, internet accessibility, institutional resources, classroom equipment, and teacher training opportunities. While some schools located in large urban centers may benefit from relatively stable internet access, computer equipment, and institutional support, many schools situated in rural or socio-economically marginalized regions continue to experience important material and logistical limitations that restrict the effective use of educational technologies. These structural inequalities directly influence teachers' pedagogical practices and students' access to digital learning opportunities. In many cases, teachers are required to develop adaptive and improvised pedagogical strategies in order to compensate for insufficient technological resources, unstable internet connectivity, overcrowded classrooms, or limited institutional support. Such contextual realities illustrate that digital transformation in education cannot be understood solely as a technical process of equipment modernization but rather as a complex socio-pedagogical process shaped by institutional conditions, social inequalities, and local educational realities (Selwyn, 2022).

Furthermore, the Tunisian educational context has been profoundly affected by the COVID-19 pandemic, which accelerated the use of online and distance learning practices while simultaneously exposing the digital divide affecting students and schools. During periods of school closure, many teachers and students encountered serious difficulties related to internet access, digital devices, and technological preparedness. These experiences highlighted the importance of developing more inclusive and contextually

adapted digital education policies capable of addressing existing educational inequalities and infrastructural limitations. Biology education occupies a strategic position within Tunisian secondary education because it contributes not only to scientific literacy but also to environmental awareness, health education, critical thinking, and citizenship development. In a context marked by environmental crises, public health challenges, and rapid scientific and technological change, biology education plays a crucial role in helping students understand complex scientific issues related to ecology, sustainability, nutrition, genetics, and human health. Consequently, the integration of digital technologies into biology classrooms may provide important opportunities for improving scientific visualization, inquiry-based learning, experimentation, and students' engagement with scientific knowledge.

Digital technologies are particularly relevant for biology education because many biological concepts are abstract, microscopic, dynamic, and difficult to observe directly through traditional teaching methods alone. Virtual laboratories, simulations, augmented reality applications, interactive videos, and multimedia resources may therefore facilitate the visualization of complex biological phenomena and encourage more active learning approaches (Ibáñez & Delgado-Kloos, 2018). However, the pedagogical effectiveness of these technologies largely depends on teachers' professional competencies, pedagogical adaptation, and the institutional conditions within which these tools are implemented. Existing international studies mainly emphasize the positive effects of digital technologies on students' academic achievement, motivation, engagement, and collaborative learning (Sailer & Homner, 2020; Bond et al., 2021). Nevertheless, fewer studies critically explore how teachers adapt digital pedagogical practices to structurally constrained educational environments characterized by unequal resources and institutional limitations. Many studies also tend to focus primarily on technological tools themselves rather than on teachers' lived experiences, contextual adaptation strategies, pedagogical negotiations, and the broader socio-economic realities shaping classroom practices.

Moreover, limited research has specifically examined how Tunisian biology teachers perceive educational digitalization, how they integrate digital technologies into their daily pedagogical practices, and how they navigate the tensions between institutional expectations and contextual constraints. Understanding these dimensions appears particularly important because teachers constitute central actors in the success or failure of educational digitalization processes. Their perceptions, competencies, professional experiences, and adaptive practices significantly influence the ways digital technologies are implemented and appropriated within classrooms. There is consequently a need for context-sensitive research capable of analyzing not only the pedagogical opportunities associated with digital technologies but also the institutional, technological, pedagogical, and socio-economic challenges shaping digital practices in Tunisian biology education. Examining teachers' experiences, perceptions, and adaptation strategies may therefore contribute to a more nuanced understanding of educational digitalization processes in Tunisia and provide valuable insights for the development of more equitable, inclusive, and contextually adapted digital education policies.

1.4. Research Objectives and Significance of the Study

This study aims to explore the integration of digital technologies in biology education within Tunisian secondary schools, with particular attention to the opportunities and challenges associated with their pedagogical use. More specifically, the research seeks to analyze biology teachers' perceptions of digital technologies, identify the pedagogical practices developed in biology classrooms, and examine the structural, institutional, technological, and socio-economic factors influencing technology integration in secondary education. The study also aims to understand how teachers adapt digital tools and pedagogical practices to local educational realities characterized by unequal resources, infrastructural limitations, diverse socio-economic conditions, and varying levels of institutional support. Particular attention is devoted to teachers' adaptive strategies, professional experiences, and pedagogical negotiations in contexts where digital integration often depends on individual initiative, pedagogical creativity, and informal problem-solving practices rather than on stable institutional resources. By investigating teachers' experiences and contextual adaptation strategies, this research intends to provide a more nuanced and situated understanding of educational digitalization processes in Tunisia.

In addition, the study seeks to examine how digital technologies influence teaching methods, classroom interactions, students' engagement, inquiry-based learning practices, and scientific reasoning in

biology education. Because biology teaching frequently involves abstract, microscopic, dynamic, and experimentally complex scientific phenomena, the integration of digital technologies may contribute to improving visualization, experimentation, conceptual understanding, and collaborative learning processes (Ibáñez & Delgado-Kloos, 2018). Virtual laboratories, simulations, multimedia resources, and interactive educational platforms may facilitate students' understanding of complex biological concepts while promoting more active and student-centered pedagogical approaches. The research also aims to explore the tensions that may emerge between educational digitalization policies and classroom realities. Although educational institutions increasingly promote the integration of ICT as a means of pedagogical innovation and modernization, teachers frequently encounter practical challenges related to inadequate technological infrastructure, insufficient training, unstable internet access, overcrowded classrooms, and limited institutional support. Examining these tensions may provide important insights into the gap that often exists between institutional discourses on digital transformation and the concrete realities of educational practice within developing educational systems.

Another objective of the study is to analyze how educational inequalities influence access to digital learning opportunities in Tunisian secondary schools. The research therefore seeks to examine the ways socio-economic disparities, regional inequalities, and infrastructural differences shape teachers' pedagogical practices and students' experiences with educational technologies. Such analysis appears particularly important in contexts where digital transformation processes risk reinforcing pre-existing educational inequalities between schools, regions, and social groups. The significance of this study is both theoretical and practical. From a theoretical perspective, the research contributes to the growing international literature on digital education and science education by providing empirical evidence from a relatively underexplored Global South context (Selwyn, 2022). While many international studies focus primarily on technologically advanced educational systems, this study emphasizes the importance of contextual realities, institutional inequalities, and local adaptation processes in shaping educational digitalization.

It therefore enriches critical discussions concerning the relationships between technological innovation, pedagogical transformation, contextual adaptation, and educational inequalities. The study also contributes to broader reflections on digital transformation in education by challenging technologically deterministic perspectives that present digitalization as an inherently positive or universally applicable process. Instead, the research highlights the complex interactions between technological tools, pedagogical practices, institutional environments, socio-economic conditions, and cultural realities. In doing so, it promotes a more critical, reflexive, and context-sensitive understanding of educational innovation within developing educational systems. Furthermore, this research contributes to the field of biology education by examining how digital technologies may transform the teaching and learning of scientific knowledge in secondary schools. While numerous studies discuss digital education in general terms, fewer studies specifically investigate the pedagogical implications of digital technologies within biology education, particularly in North African contexts. The present study therefore seeks to fill an important empirical and theoretical gap in the existing literature. From a practical perspective, the findings may support policymakers, teacher educators, curriculum designers, and educational institutions in developing more context-sensitive digital education policies and pedagogical strategies. The study may contribute to improving teacher training programs by identifying the professional competencies, pedagogical needs, and institutional support mechanisms necessary for effective digital integration in biology education. It may also help educational stakeholders better understand the realities, constraints, and adaptation strategies experienced by teachers in their daily pedagogical practices. Moreover, the research may provide useful insights for strengthening institutional support systems and reducing educational inequalities related to technological access and digital learning opportunities. By highlighting disparities affecting schools and regions, the study may contribute to promoting more equitable access to digital resources and more inclusive educational policies. The findings may also support policymakers in developing educational strategies better adapted to local realities and teachers' needs. Ultimately, this research seeks to promote a more inclusive, pedagogically meaningful, and context-sensitive integration of digital technologies in biology education, emphasizing educational equity alongside technological innovation.

1.5. Research Questions

Based on the objectives and contextual issues discussed above, this study is guided by the following research questions, which focus on the pedagogical integration of digital technologies, their educational contributions, and the constraints shaping their use in Tunisian biology education:

1. How are digital technologies integrated into biology teaching practices in Tunisian secondary schools, and how do teachers operationalize these tools in classroom settings?
2. What pedagogical opportunities and learning benefits do digital technologies provide for biology education, particularly in terms of students' engagement, conceptual understanding, scientific reasoning, and inquiry-based learning?
3. What institutional, pedagogical, technological, and socio-economic factors facilitate or hinder the effective integration of digital technologies in biology education in Tunisia, and how do teachers adapt to these constraints in their professional practice?

Moreover, these questions aim to capture the complex interaction between technology, pedagogy, and context in shaping classroom practices. They also seek to highlight teachers' lived experiences as central actors in the digital transformation of education. Ultimately, they provide a framework for understanding how meaningful and equitable digital integration can be achieved in biology education. This analytical framework also helps to better situate educational digitalization within broader issues of equity, inclusion, pedagogical quality, and sustainable educational development in contemporary science education systems.

2. METHODOLOGY

This study adopts a qualitative research methodology in order to explore the integration of digital technologies in biology education within Tunisian secondary schools. A qualitative approach was considered particularly appropriate because the research seeks to understand teachers' lived experiences, pedagogical practices, perceptions, and contextual adaptation strategies regarding the use of digital technologies in biology classrooms. Unlike quantitative approaches that primarily focus on measurement and statistical generalization, qualitative research allows for an in-depth exploration of complex educational phenomena situated within specific institutional, socio-economic, and pedagogical contexts (Creswell & Poth, 2018; Merriam & Tisdell, 2021). Recent studies in digital education emphasize the importance of qualitative and context-sensitive approaches for understanding how teachers negotiate technological innovation within unequal educational environments (Selwyn, 2022; Williamson & Hogan, 2020).

The study therefore aims to provide a situated and reflexive understanding of how biology teachers experience educational digitalization and negotiate the opportunities and challenges associated with technology integration in their daily professional practices. In order to reduce risks of descriptive reproduction and ensure originality, the methodology was developed through a contextualized analytical framework specifically adapted to Tunisian secondary education realities and informed by recent literature on digital pedagogy, inquiry-based science education, and educational inequalities. The methodological design combines semi-structured interviews, classroom observations, and document analysis in order to ensure methodological triangulation and strengthen the credibility, validity, and analytical richness of the findings (Denzin, 2017; Braun & Clarke, 2021). This multi-method qualitative strategy makes it possible to examine digital pedagogical practices from multiple perspectives while capturing the interactions between technological tools, institutional realities, classroom dynamics, and socio-economic conditions. The methodology was also designed to account for contextual variations between schools characterized by different levels of technological infrastructure, internet accessibility, and institutional support for ICT integration.

2.1. Research Design

The study employs an exploratory qualitative multiple-case study design. This research design was selected because it enables the detailed investigation of educational practices within their real-life institutional and pedagogical contexts (Yin, 2018). Multiple-case studies are particularly relevant for examining educational innovation processes across diverse institutional environments because they allow

researchers to compare similarities and contextual differences between cases while identifying recurring pedagogical patterns (Stake, 2006). In the present study, the multiple-case approach facilitates the examination of how digital technologies are integrated into biology education across Tunisian secondary schools characterized by varying socio-economic conditions, technological infrastructures, and geographical locations. Furthermore, this design makes it possible to capture the complexity of teachers' adaptive strategies and the contextual realities shaping digital pedagogical practices in resource-constrained educational environments. It also contributes to developing a more nuanced understanding of the interactions between educational policies, institutional conditions, and classroom-level experiences related to technology integration in biology education.

The research is grounded in an interpretivist epistemological perspective, which assumes that educational realities are socially and institutionally constructed through teachers' experiences, professional interactions, pedagogical negotiations, and contextual constraints (Merriam & Tisdell, 2021). From this perspective, the integration of digital technologies is understood not merely as a technical modernization process but rather as a complex socio-pedagogical transformation shaped by institutional conditions, educational inequalities, teachers' agency, and local adaptation strategies (Selwyn, 2022). Recent literature on educational digitalization further highlights that technological innovation cannot be separated from broader questions related to equity, access, and pedagogical meaning-making (UNESCO, 2023; OECD, 2024). A qualitative exploratory design was therefore considered particularly suitable because the study seeks to investigate teachers' perceptions, classroom experiences, adaptive strategies, and professional practices in depth rather than to establish statistical generalizations. This methodological orientation also aligns with recent calls for more context-sensitive research on educational technologies in Global South contexts, where digital transformation processes are often shaped by infrastructural limitations, socio-economic disparities, and institutional inequalities (World Bank, 2024).

2.2. Participants

The participants in this study consisted of biology teachers working in Tunisian public secondary schools. A purposive sampling strategy was employed to select participants who had direct and relevant experience with the use of digital technologies in biology teaching and who could provide rich, diverse, and contextually grounded information about the phenomenon under investigation (Patton, 2015). Purposeful sampling is particularly appropriate in qualitative educational research because it enables researchers to identify participants with specific experiences and knowledge relevant to the research questions (Creswell & Poth, 2018). A total of 18 biology teachers participated in the study. Participants were recruited from public secondary schools located in different Tunisian regions and representing urban, semi-urban, and rural contexts. This contextual diversity was intentionally sought because the integration of digital technologies may be influenced by differences in school infrastructure, internet connectivity, availability of technological equipment, access to digital educational resources, and institutional support. Including teachers working in different school environments therefore enabled the study to capture a broader range of experiences and perspectives concerning the opportunities and constraints associated with digital technology integration in biology education.

The participating teachers were aged between 28 and 56 years, while their professional experience ranged from 3 to 28 years. This variation in age and teaching experience provided an opportunity to consider differences in teachers' professional trajectories, digital competencies, pedagogical practices, and attitudes toward educational technologies. The sample included 9 male and 9 female teachers, providing balanced representation by gender. The participants also differed in their levels of exposure to digital technologies and in the technological conditions of their schools. According to the data collected, 11 teachers (61.11%) reported using digital platforms regularly, whereas 7 teachers (38.89%) reported limited access to technological resources. These differences were considered relevant to understanding how institutional and contextual conditions shape teachers' digital practices. The selection of participants followed several inclusion considerations. Teachers were required to be currently teaching biology in a Tunisian public secondary school and to have sufficient professional experience to provide informed accounts of their teaching practices. Particular attention was given to including teachers with different levels of professional experience and working in schools with varying degrees of technological provision. This strategy aimed to maximize the diversity of perspectives rather than statistical representativeness, which is

consistent with the logic of purposive sampling in qualitative research. Participants were recruited through direct communication with school administrations and voluntary participation procedures. Before data collection, each participant received clear information about the purpose and scope of the study, the nature of their participation, the data collection procedures, and the measures adopted to protect confidentiality. Participants were also informed that participation was voluntary and that they could withdraw from the study at any stage without negative consequences. Written informed consent was obtained from all participants before the interviews and classroom observations were conducted. To ensure confidentiality and anonymity, participants were assigned pseudonyms or identification codes during data transcription, coding, analysis, and reporting. No personally identifiable information was included in the presentation of the findings. The same confidentiality procedures were applied to the classroom observations and interview materials. These measures were intended to create conditions in which participants could describe their experiences, perceptions, and professional practices openly, particularly when discussing institutional constraints and technological difficulties. Overall, the composition of the sample was designed to provide contextual and experiential diversity rather than statistical generalization. The combination of differences in age, professional experience, gender, school location, technological access, and reported use of digital platforms provided a sufficiently varied qualitative corpus for examining how biology teachers experience and adapt to the integration of digital technologies within different Tunisian secondary school contexts.

Table 1. Participants' Characteristics

Participants' Characteristics	Number	Percent
Male Teachers	9	50.00
Female Teachers	9	50.00
Age range (e.g., 28–56 years)	18	100.00
Urban Secondary Schools	7	38.89
Semi-Urban Secondary Schools	5	27.78
Rural Secondary Schools	6	33.33
Teaching Experience (3–10 years)	6	33.33
Teaching Experience (11–20years)	7	38.89
Teaching Experience (21–28years)	5	27.78
Teachers Using Digital Platforms Regularly	11	61.11
Teachers Reporting Limited Technological Access	7	38.89
Total Participants	18	100.00

2.3. Research Instruments

Data were collected using three complementary qualitative research instruments: semi-structured interviews, classroom observations, and document analysis. These instruments were developed specifically for the present study rather than directly adopted from a previously validated instrument. Their design was informed by the research objectives and by relevant literature on digital technology integration, biology education, inquiry-based learning, and educational technology (Bond et al., 2021; Tondeur et al., 2021). The combination of the three instruments enabled methodological triangulation by allowing the researcher to compare teachers' reported practices with observed classroom practices and relevant institutional and pedagogical documents. This triangulation contributed to strengthening the credibility and analytical depth of the findings (Denzin, 2017; Flick, 2022).

2.3.1. Semi-Structured Interviews

Semi-structured interviews constituted the primary data collection instrument and were designed to obtain detailed information about biology teachers' experiences, perceptions, practices, and challenges regarding the integration of digital technologies into their teaching. A specific interview guide consisting of 12 open-ended questions was developed for the present study. The guide was constructed in accordance with the research objectives and informed by relevant literature on digital technology integration, science education, inquiry-based learning, and teachers' professional development. Rather than being directly adopted from a previously validated instrument, the interview guide was specifically developed for the Tunisian educational context. The 12 questions were organized around five complementary thematic dimensions:

1. teachers' perceptions and uses of digital technologies.
2. pedagogical benefits and student engagement.
3. classroom practices and technological adaptation.
4. institutional and technological constraints.
5. professional development and training needs.

This organization ensured that the interviews addressed both the pedagogical dimensions of digital technology use and the contextual conditions influencing its implementation. The first dimension explored teachers' general perceptions of digital technologies and the types of tools they used in biology teaching. Questions addressed the frequency and purposes of technology use, including digital platforms, multimedia resources, educational videos, simulations, virtual laboratories, online scientific resources, and interactive learning applications. The second dimension examined teachers' perceptions of the pedagogical contribution of digital technologies, particularly their potential to facilitate the visualization of biological processes, increase student engagement, support scientific understanding, and promote interactive learning. The third dimension focused on actual classroom practices and teachers' strategies for adapting digital technologies to different teaching situations. Participants were invited to describe specific classroom experiences and explain how they integrated digital resources into lesson objectives, activities, assessment, inquiry-based learning, and collaborative learning. The interviews also explored teachers' experiences during and after the COVID-19 pandemic, particularly the development or modification of online and technology-supported teaching practices. The fourth dimension addressed institutional and technological constraints affecting digital integration. Questions explored issues such as the availability and reliability of technological equipment, internet connectivity, access to digital resources, technical support, classroom conditions, time constraints, and differences between schools. Participants were also encouraged to describe concrete situations in which technological limitations affected their teaching practices and the strategies they adopted to overcome such difficulties. The fifth dimension examined teachers' professional development needs and the forms of institutional support required to strengthen digital technology integration. Participants were asked to discuss their previous training, perceived gaps in digital competencies, preferred forms of professional development, and the types of institutional or technical support that could facilitate more effective and sustainable technology use.

Examples of the interview questions included: (1) *What digital technologies do you regularly use in your biology classes, and for what purposes?*; (2) *How do digital technologies influence students' engagement and participation?*; (3) *How do digital resources help students understand or visualize biological processes?*; (4) *What difficulties do you encounter when integrating digital technologies into your biology teaching?*; (5) *How do you adapt your teaching practices when technological resources or internet connectivity are limited?*; and (6) *What types of professional training or institutional support would facilitate your use of digital technologies?* These questions were complemented by follow-up prompts when necessary to encourage participants to clarify their responses, provide concrete examples, or elaborate on particular experiences.

The semi-structured format provided a balance between consistency and flexibility. The same core questions were addressed to all participants, thereby ensuring comparability across interviews, while the interviewer was able to modify the order of questions, ask follow-up questions, and explore emerging issues according to each participant's responses. This approach was particularly useful for capturing the diversity of teachers' experiences across different school contexts and levels of technological access. A total of 18 biology teachers participated in the interviews. Each interview lasted between 45 and 75 minutes and was conducted either face-to-face or online, depending on participants' availability, preferences, and institutional conditions. Before each interview, participants were reminded of the purpose of the study, the voluntary nature of their participation, and the confidentiality of the information provided. With participants' informed consent, all interviews were audio-recorded to ensure accurate data collection. The recordings were subsequently transcribed verbatim, and the transcripts were carefully checked against the original recordings to minimize transcription errors. Following transcription, the interview data were anonymized through the use of pseudonyms or participant codes. The transcripts were then prepared for thematic analysis by identifying meaningful units of information related to the research questions and the main thematic dimensions of the interview guide. The interview findings were subsequently compared with classroom observation records and documentary evidence, allowing the researcher to identify convergences,

complementarities, and potential discrepancies between teachers' reported practices, observed classroom practices, and institutional expectations. This process contributed to methodological triangulation and strengthened the credibility of the qualitative interpretation.

2.3.2. Classroom Observations

Classroom observations were conducted to examine how digital technologies were actually implemented in biology teaching and to compare observed practices with teachers' reported experiences during the semi-structured interviews. A structured observation protocol was developed specifically for this study and applied consistently across all observation sessions. The protocol was designed in accordance with the research objectives and focused on the pedagogical, technological, and interactional dimensions of digital technology integration in biology classrooms. The observation protocol covered seven main dimensions:

1. The types and purposes of digital tools used.
2. The pedagogical strategies adopted by teachers.
3. Students' engagement and participation.
4. Inquiry-based learning activities.
5. Teacher–student interactions.
6. Collaborative learning dynamics.
7. Technological difficulties and teachers' adaptive strategies.

These dimensions were selected to capture not only the presence of digital technologies but also the ways in which they were pedagogically integrated into classroom activities. The first dimension focused on the types of technologies and digital resources used during lessons, such as computers, projectors, interactive digital resources, educational platforms, multimedia materials, simulations, videos, and online scientific resources. Attention was also given to the pedagogical purpose of each tool, including content presentation, visualization of biological processes, explanation of complex concepts, student exploration, assessment, communication, and collaborative learning. The second dimension examined teachers' pedagogical strategies and the extent to which digital technologies were integrated into the learning objectives and lesson activities. Particular attention was paid to whether teachers used digital resources primarily for transmitting information or whether they encouraged students to explore, investigate, formulate questions, interpret information, solve problems, and construct scientific explanations. The observation also considered the teacher's role in guiding students' use of digital resources and adapting activities to students' learning needs. The third dimension concerned students' engagement and participation. The researcher documented students' level of attention, participation in digital activities, interaction with learning resources, willingness to ask or answer questions, and degree of autonomy when using digital tools. Observable indicators of active participation, distraction, difficulties in using technologies, and differences in students' access to or familiarity with digital resources were also noted. The fourth dimension focused on inquiry-based learning activities. Observations examined whether digital technologies were used to support scientific questioning, hypothesis generation, information searching, data interpretation, experimentation, simulation, problem-solving, and the development of evidence-based explanations. Particular attention was given to the extent to which digital resources enabled students to engage actively with biological phenomena rather than simply receive information.

The fifth dimension addressed teacher–student interactions, including the ways teachers introduced and explained digital resources, provided technical or pedagogical guidance, responded to students' questions, and monitored their learning. The observation also considered how digital technologies influenced classroom communication and whether they facilitated more interactive exchanges between teachers and students. The sixth dimension examined collaborative learning dynamics. The researcher recorded whether students worked individually, in pairs, or in groups when using digital technologies, as well as the nature of peer interaction, information sharing, joint problem-solving, and collaborative task completion. Attention was also given to the distribution of participation within groups and to the role of digital resources in supporting collective learning. The seventh dimension concerned technological

difficulties and teachers' adaptive strategies. The researcher documented problems related to internet connectivity, equipment availability, software access, technical failures, electricity interruptions, and students' access to digital resources. The ways in which teachers responded to these difficulties, such as modifying activities, using alternative resources, relying on offline materials, or reorganizing classroom tasks, were also recorded. For each dimension, the researcher recorded the presence, frequency, and nature of relevant practices whenever observable, supported by detailed field notes. The notes included descriptions of classroom activities, teacher and student interactions, technological resources used, students' responses, contextual conditions, and teachers' responses to technological constraints. Particular attention was given to the relationship between the intended pedagogical objectives and the actual use of digital technologies during the lesson.

A total of 12 biology lessons were observed across the participating schools. Each observation lasted approximately 50 to 60 minutes, corresponding to regular classroom periods. The observations were non-participant: the researcher remained in an observational position and did not intervene in teaching activities or interact directly with students during the lessons. This approach was adopted to minimize disruption and to capture classroom practices under relatively natural conditions. Before each observation, contextual information such as the school setting, lesson topic, available technological resources, and planned use of digital technologies was documented when available. During the lesson, the researcher systematically recorded relevant observations using the protocol and supplemented the predefined categories with descriptive field notes. Immediately after each observation, the field notes were reviewed and expanded to clarify contextual details, significant classroom events, technological problems, and emerging observations. These records were subsequently organized and coded thematically alongside the interview data and documentary material. The observation data therefore provided direct evidence of how digital technologies were used in authentic biology classrooms and helped identify possible differences between teachers' stated practices and their actual classroom implementation. Combined with interviews and document analysis, classroom observations contributed to methodological triangulation and strengthened the interpretation of the findings concerning the opportunities, limitations, and contextual conditions associated with digital technology integration in Tunisian biology education.

2.3.3. Document Analysis

Document analysis was used as a complementary qualitative research instrument to examine the institutional, curricular, and pedagogical context of digital technology integration in Tunisian secondary biology education. The document analysis protocol was developed specifically for the present study in accordance with the research objectives and the main themes addressed in the interviews and classroom observations. The use of documentary evidence made it possible to examine not only teachers' reported practices and observed classroom activities but also the formal recommendations, expectations, and resources that frame digital technology integration within the Tunisian educational system. The documentary corpus was purposively selected according to three main criteria:

1. Relevance to biology education or educational digitalization.
2. Direct relationship with the integration or use of ICT and digital resources in secondary education.
3. Potential contribution to understanding the institutional and pedagogical conditions influencing teachers' practices.

The corpus included official curriculum guidelines, institutional documents related to ICT integration, teacher training materials, digital educational resources, lesson plans, teaching guides, and pedagogical materials used by participating teachers. Documents were retained when they contained explicit or implicit information concerning the objectives, recommended uses, pedagogical functions, or institutional conditions associated with digital technology in teaching and learning. The analysis was guided by a predefined documentary analysis framework comprising seven complementary criteria: (1) the objectives and purposes assigned to digital technology use; (2) the types and functions of digital resources recommended or employed; (3) the expected roles of teachers and students; (4) opportunities for interactive, collaborative, and inquiry-based learning; (5) pedagogical recommendations concerning the integration of digital technologies into teaching and learning activities; (6) technological, infrastructural, and professional requirements; and (7) the degree of alignment between institutional recommendations and

observed classroom practices. The first criterion examined how digital technologies were presented in official and pedagogical documents, particularly whether they were intended primarily to support content delivery, scientific visualization, communication, assessment, student exploration, or inquiry-based learning. The second criterion focused on the types of digital resources mentioned or provided, including digital platforms, multimedia resources, simulations, videos, online resources, and other technology-supported learning materials. The third criterion examined the roles attributed to teachers and students, with particular attention to expectations concerning student autonomy, active participation, collaboration, and teachers' pedagogical mediation. The fourth criterion focused on the extent to which the documents promoted interactive, collaborative, and inquiry-based approaches. The fifth examined specific pedagogical recommendations, including suggested activities, learning objectives, and conditions for the effective use of digital resources. The sixth criterion addressed the technological and professional conditions required for implementation, such as access to equipment, internet connectivity, digital competencies, teacher training, and technical support. Finally, the seventh criterion enabled comparison between formal institutional expectations and the practices documented through classroom observations and teachers' accounts.

The analysis followed a systematic process. First, the selected documents were reviewed and organized according to their type, source, educational level, and relevance to the research questions. Second, relevant passages and sections were identified and coded according to the predefined criteria. Third, emerging patterns, recurring themes, and discrepancies were examined across different types of documents. Particular attention was given to differences between formal recommendations and the practical conditions reported by teachers or observed in classrooms. This process made it possible to identify areas of convergence as well as potential gaps between policy intentions, curricular expectations, available pedagogical resources, and actual classroom implementation. Document analysis also provided an important contextual basis for interpreting the interview and observation findings. For example, when teachers reported difficulties related to infrastructure, training, or access to digital resources, documentary evidence was examined to determine whether such conditions were reflected in institutional policies, training provisions, curriculum guidelines, or available educational resources. Similarly, when digital technologies were observed being used for visualization, collaboration, or inquiry-based activities, relevant curricular and pedagogical documents were examined to assess the extent to which such practices were institutionally encouraged. To enhance the credibility of the analysis, documentary evidence was not considered independently but was systematically compared with the two other sources of qualitative data. Interviews provided access to teachers' perceptions and experiences, classroom observations documented actual pedagogical practices, and document analysis provided information about the curricular and institutional framework within which these practices occurred. Convergences across the three sources strengthened the interpretation of recurrent findings, whereas discrepancies were examined as potentially meaningful evidence of differences between policy expectations, teachers' perceptions, and classroom realities. This triangulation contributed to a more comprehensive understanding of digital technology integration in Tunisian biology education. It also helped situate teachers' practices within the broader institutional and curricular context and reduced reliance on a single source of evidence. In this respect, document analysis was particularly valuable for examining the relationship between educational policies, institutional expectations, pedagogical resources, and classroom implementation processes (Bowen, 2009; OECD, 2024).

2.4. Procedures

The research was conducted over a six-month period, from September 2025 to February 2026. Data collection followed a series of successive and interconnected stages designed to ensure methodological rigor, ethical compliance, and consistency across the different sources of evidence. The procedure was organized around four main stages: institutional authorization and participant recruitment, semi-structured interviews, classroom observations, and documentary collection and analysis. The first stage involved obtaining the necessary institutional authorization from the administrations of the participating schools. Before data collection began, the researcher explained the objectives, scope, procedures, and ethical principles of the study to the school administrations and participating teachers. Biology teachers were contacted individually and invited to participate voluntarily. Participants were informed that their involvement was entirely voluntary and that the information collected would be used exclusively for

research purposes. Informed consent forms were provided and signed before any interview or classroom observation was conducted. Participants were also informed of their right to withdraw from the study at any stage without providing a justification. The second stage consisted of conducting semi-structured interviews with the participating biology teachers. All interviews were conducted face-to-face, rather than online, in locations agreed upon with the participants and allowing sufficient privacy and freedom of expression. The interviews were scheduled according to teachers' professional availability and were generally conducted in quiet spaces within the school or in other appropriate settings. The semi-structured format provided sufficient consistency across interviews while allowing the researcher to explore emerging issues, clarify participants' responses, and obtain detailed accounts of their experiences with digital technologies in biology teaching. The interviews addressed several dimensions, including teachers' uses of digital technologies, perceived pedagogical benefits, difficulties encountered, access to technological resources, professional training, and the conditions influencing technology integration. With participants' consent, all interviews were audio-recorded. The recordings were securely stored and subsequently transcribed verbatim. During the transcription process, identifying information was removed or anonymized to protect participants' identities and ensure confidentiality.

The third stage involved systematic classroom observations. Observation sessions were organized in collaboration with participating teachers and school administrations and were conducted during regular biology lessons. The researcher adopted a non-participant observer position in order to minimize interference with normal classroom activities and preserve the natural character of teacher–student interactions. Particular attention was paid to the types of digital technologies used, the purposes for which they were employed, the pedagogical strategies associated with their use, teacher–student and student–student interactions, students' engagement, and the difficulties or technical constraints observed during the lessons. Detailed field notes were recorded systematically during each observation and completed immediately afterwards in order to document contextual information and relevant pedagogical events that might not have been captured during the lesson itself. The fourth stage concerned the collection and examination of institutional and pedagogical documents related to digital education and biology teaching. Documents were collected from participating schools, official educational platforms, and participating teachers. The documentary corpus included relevant institutional documents, educational guidelines, digital education materials, pedagogical resources, and documents used by teachers in connection with biology instruction. The documents were reviewed using a systematic documentary analysis procedure. First, the collected materials were screened according to their relevance to the research objectives. Second, relevant sections were identified and extracted. Third, the documents were coded according to analytical categories derived from the research questions, including the objectives of digital education, the prescribed uses of digital technologies, their pedagogical functions, the resources available to teachers, and the conditions and constraints associated with their implementation. Finally, the coded information was organized thematically and compared with evidence obtained from the interviews and classroom observations. This process made it possible to identify convergences, complementarities, and discrepancies between prescribed policies, teachers' reported practices, and observed classroom practices.

The different stages of data collection were closely interconnected. Information emerging from the interviews helped guide attention during classroom observations, while observations provided contextual elements for interpreting teachers' accounts. Similarly, documentary analysis provided an institutional and curricular framework for understanding the practices reported and observed in schools. The combination of these complementary sources contributed to the triangulation of the findings and strengthened the credibility and contextual interpretation of the results. Ethical considerations constituted an integral component of the research process. Participants' anonymity, confidentiality, and professional privacy were strictly respected throughout all stages of the study. No identifiable information was included in the research database or reported in the findings. Audio recordings, interview transcripts, observation notes, and documentary materials were securely stored and were accessible only for research purposes. The data were used exclusively for academic purposes and handled in accordance with established ethical principles for educational research. In accordance with the principles of the British Educational Research Association (BERA, 2024), participants were informed of their rights and retained the right to withdraw from the study at any stage without providing a justification.

2.5. Data Analysis

The collected qualitative data were analyzed using thematic analysis, a widely established methodological approach in qualitative educational research for identifying, organizing, interpreting, and reporting meaningful patterns within complex datasets (Braun & Clarke, 2021). Thematic analysis was selected because of its flexibility and analytical rigor, allowing the researchers to capture participants' experiences, perceptions, pedagogical practices, and contextual realities concerning the integration of digital technologies into biology education. The analysis was conducted iteratively, with continuous movement between the empirical data, emerging codes, thematic categories, and the research questions. The analysis process began with the preparation and organization of the qualitative corpus. Interview recordings were transcribed, while classroom observation notes and institutional and pedagogical documents were compiled and organized according to their respective sources. All materials were anonymized before analysis to protect participants' identities and ensure confidentiality. The two researchers then independently read the entire corpus several times to achieve a high level of familiarity with the data and to develop an initial understanding of recurrent ideas, significant statements, contextual particularities, and emerging patterns. During this familiarization stage, preliminary analytical notes and reflexive observations were recorded. The second stage involved initial open coding. The two researchers independently coded relevant segments of the interview transcripts, classroom observation notes, and documentary materials. Coding was conducted at the level of meaningful units of information rather than isolated words, allowing the researchers to preserve the contextual meaning of participants' statements and observed practices. The coding process focused on issues directly related to the research objectives, including digital technology integration, pedagogical innovation, teachers' professional practices, students' engagement, inquiry-based learning, infrastructural limitations, technological inequalities, adaptive strategies, professional development, and institutional support. Both descriptive and interpretive codes were considered in order to distinguish between what participants reported or what was observed and the underlying meanings emerging from the data.

The coding process was conducted by two researchers using a common initial coding framework. Each researcher independently coded the relevant sections of the corpus and subsequently compared their coding decisions. Particular attention was given to differences in the interpretation, labeling, or categorization of specific excerpts. Discrepancies were discussed systematically and resolved through discussion and consensus. When disagreement persisted, the researchers returned to the original transcript, observation note, or document and reconsidered the excerpt in relation to the research questions and theoretical framework. Codes were subsequently redefined, merged, separated, or renamed when necessary. This iterative comparison and consensus-building procedure contributed to improving the conceptual clarity, consistency, and credibility of the coding process. In the third stage, related codes were compared and grouped into broader categories. The researchers examined similarities, differences, relationships, and recurrent patterns across participants and across the three main sources of data. This process made it possible to move progressively from descriptive codes toward more interpretive thematic categories. Particular attention was paid to both convergent and divergent evidence in order to avoid reducing the analysis to dominant or frequently expressed viewpoints. The emerging categories were continuously compared with the original data to ensure that the developing interpretations remained grounded in the empirical material.

In the fourth stage, broader thematic patterns were identified and developed into preliminary themes. Examples of emerging themes included digital pedagogical innovation, technological inequalities, professional adaptation strategies, student engagement, infrastructural challenges, institutional constraints, and teachers' professional development needs. Each preliminary theme was examined in terms of its internal coherence and its distinction from other themes. Themes that contained conceptually similar material were merged, while themes that were too broad or heterogeneous were refined or divided into more specific analytical categories. The fifth stage involved reviewing and refining the thematic structure. The two researchers revisited the coded extracts associated with each theme and then returned to the dataset as a whole to determine whether the thematic framework adequately represented the range and complexity of the data. Themes were retained when they were sufficiently supported by the empirical evidence and directly relevant to the research questions. This process also involved identifying negative cases, contrasting experiences, and contextual variations between schools and participants. The final thematic structure was therefore not based solely on the frequency of particular responses but also on their analytical relevance.

and explanatory value. The sixth stage consisted of interpreting the finalized themes in relation to the research questions and the theoretical framework guiding the study. The analysis sought to establish relationships between teachers' reported practices, observed classroom practices, and institutional conditions. Particular attention was given to the relationship between pedagogical opportunities offered by digital technologies and the structural, technological, professional, and institutional constraints that may limit their effective integration.

Data triangulation was used to strengthen the credibility and trustworthiness of the findings (Flick, 2022). Evidence from semi-structured interviews was systematically compared with classroom observations and documentary materials. This triangulation made it possible to identify areas of convergence between teachers' reported practices and observed practices, as well as discrepancies that could provide additional insight into the contextual conditions influencing digital technology integration. Documentary evidence was used to contextualize teachers' accounts and observed classroom practices within the broader institutional and educational framework. In addition, member-checking procedures were conducted with several participants to assess the plausibility and accuracy of selected thematic interpretations. Participants were invited to comment on whether the interpretations adequately reflected their experiences and perspectives. Their feedback was considered during the refinement of the analytical categories and themes. Reflexive analytical practices were maintained throughout the research process. The researchers regularly examined their assumptions, interpretive decisions, and potential sources of bias in order to maintain methodological transparency and ensure that the findings remained grounded in the empirical data. Overall, the analytical process combined systematic coding, collaborative comparison, thematic development, triangulation, participant validation, and researcher reflexivity. These procedures contributed to strengthening the credibility, dependability, and interpretive depth of the findings. The analysis ultimately sought to provide a nuanced and context-sensitive understanding of how digital technologies are integrated into biology education in Tunisian secondary schools, while highlighting the interaction between pedagogical opportunities, teachers' professional practices, technological resources, institutional conditions, and structural inequalities shaping educational digitalization in the Tunisian context.

3. RESULTS

The thematic analysis of interviews, classroom observations, and institutional documents revealed important insights concerning the integration of digital technologies in biology education within Tunisian secondary schools. The findings indicate that digital technologies are progressively transforming biology teaching practices by facilitating scientific visualization, promoting students' engagement, and supporting more interactive learning environments. However, the results also demonstrate that the effectiveness of digital integration remains strongly influenced by institutional conditions, technological infrastructure, teachers' professional competencies, and socio-economic inequalities affecting schools and students. Three major themes emerged from the analysis. The first theme concerns the pedagogical uses of digital technologies in biology classrooms. The second theme examines the educational opportunities and learning benefits associated with digital integration. The third theme explores the institutional, technological, and socio-economic challenges affecting the implementation of digital pedagogical practices in Tunisian secondary schools. Overall, the findings highlight that educational digitalization in biology education constitutes both a pedagogical opportunity and a structural challenge within the Tunisian educational system. They further demonstrate the necessity of developing more equitable, context-sensitive, and sustainable digital education policies capable of supporting teachers' professional practices while reducing technological and socio-economic disparities between schools and learners.

3.1. Pedagogical Uses of Digital Technologies in Biology Education

The findings reveal that biology teachers increasingly integrate digital technologies into their classroom practices in order to improve teaching effectiveness and facilitate students' understanding of complex scientific concepts. Participants reported using various digital tools, including multimedia presentations, educational videos, online scientific resources, interactive animations, virtual simulations, and digital communication platforms. These technologies were primarily employed to support scientific explanation, improve visualization of biological processes, and diversify teaching methods. Teachers

emphasized that digital technologies are particularly useful for teaching abstract and microscopic biological concepts that are difficult to explain through traditional pedagogical approaches alone. Topics such as genetics, cellular division, molecular biology, ecological systems, and human physiology were frequently identified as areas where digital visualization significantly improved students' comprehension. One participant explained that animations and simulations help students better understand biological processes that cannot be directly observed in ordinary classroom settings.

Table 2. Main Digital Technologies Used in Biology Education

Digital Tool	Number	Percent
Educational Videos	16	88.9
PowerPoint Presentations	16	88.9
Online Scientific Resources	12	66.7
Virtual Simulations	11	61.1
Interactive Educational Platforms	10	55.6
Virtual Laboratories	6	33.3
Augmented Reality Applications	3	16.7

Classroom observations confirmed that multimedia resources were regularly integrated into biology lessons. In several observed classes, teachers combined traditional teaching approaches with digital materials such as videos, PowerPoint presentations, online diagrams, and scientific animations. These pedagogical combinations appeared to increase students' attention and encourage greater classroom participation. Similar findings have been reported in recent studies demonstrating that multimedia learning environments facilitate conceptual understanding and support more interactive science teaching practices (Sailer et al., 2023; OECD, 2024). The results also indicate that teachers increasingly use online educational platforms and communication applications to share pedagogical materials, assignments, and supplementary scientific resources with students. These practices became more common following the COVID-19 pandemic, which accelerated teachers' familiarity with distance learning technologies and online educational environments (UNESCO, 2023). Several participants explained that digital communication tools improved continuity between classroom learning and students' independent study outside school hours.

The analysis further demonstrates that digital technologies contributed to the diversification of pedagogical strategies in biology education. Teachers increasingly adopted student-centered approaches that encouraged active participation, collaborative learning, and inquiry-based activities. Rather than relying exclusively on traditional lecture-based instruction, several participants reported integrating interactive activities in which students explored digital simulations, analyzed scientific videos, conducted online research, and participated in collaborative problem-solving tasks. Classroom observations showed that students were generally more engaged during digitally supported activities, particularly when teachers used visual and interactive resources capable of simplifying complex biological processes. These findings align with recent international research suggesting that digital pedagogies may enhance learner autonomy, scientific reasoning, and critical thinking when integrated within active learning environments (Howard et al., 2024; Redecker, 2023). Teachers also highlighted the pedagogical importance of virtual simulations and digital experimentation tools in contexts where access to physical laboratory equipment remains limited. In several schools, particularly those facing infrastructural constraints, virtual laboratories provided alternative opportunities for demonstrating biological experiments that could not easily be conducted in ordinary classroom conditions. Participants explained that simulations enabled students to manipulate variables, observe scientific phenomena repeatedly, and engage more actively with experimental reasoning processes. Such digital experimentation practices appeared especially useful for topics involving microscopic observation, physiological mechanisms, ecological interactions, and molecular processes. Recent literature similarly emphasizes that virtual laboratories can support inquiry-based science learning by improving students' scientific visualization and experimentation opportunities while reducing material limitations (Ibáñez & Delgado-Kloos, 2018; OECD, 2024).

Furthermore, the findings indicate that digital technologies increasingly support personalized and flexible learning processes in biology education. Several teachers reported adapting digital resources according to students' learning needs, academic levels, and learning difficulties. Online videos, interactive platforms, and supplementary scientific resources were frequently used to provide additional explanations outside classroom hours, allowing students to revisit complex lessons at their own pace. Participants

explained that such practices were particularly beneficial for students experiencing difficulties understanding abstract scientific content through conventional instruction alone. Teachers also noted that digital communication platforms facilitated more regular interaction with students by enabling the sharing of assignments, corrections, scientific articles, and educational guidance beyond classroom boundaries. However, despite these pedagogical opportunities, the analysis revealed important disparities in teachers' capacity to integrate digital technologies effectively. Teachers working in urban secondary schools generally reported better access to internet connectivity, digital equipment, multimedia projectors, and institutional technological support compared to teachers in rural or socio-economically disadvantaged regions. In several rural schools, digital integration remained largely limited to basic PowerPoint presentations and occasional educational videos because of unstable internet access, insufficient equipment, and limited institutional investment. Some teachers explained that technical problems, electricity interruptions, and inadequate maintenance services frequently disrupted digitally planned lessons and discouraged more advanced forms of pedagogical innovation.

The findings also suggest that teachers' digital competencies and professional experiences significantly influenced the quality and diversity of technology integration practices (Scherer & Teo, 2019). Participants who had received prior ICT training or who regularly engaged in self-directed digital learning appeared more confident in using interactive technologies and designing digitally supported pedagogical activities. Conversely, some teachers reported difficulties adapting to rapidly evolving digital environments, particularly when institutional training opportunities remained limited. In response to these challenges, many participants developed informal adaptation strategies based on peer collaboration, self-training, experimentation, and online professional learning communities. These adaptive practices illustrate the important role of teachers' agency and pedagogical creativity in sustaining digital integration within structurally constrained educational contexts. Moreover, the results reveal that educational digitalization in biology classrooms should not be understood solely as a process of technological modernization but rather as a broader pedagogical and institutional transformation shaped by contextual realities, infrastructural inequalities, and professional adaptation processes. While digital technologies created important opportunities for improving scientific visualization, student engagement, and pedagogical innovation, their integration remained uneven and highly dependent on institutional support, socio-economic conditions, and teachers' professional capacities. These findings therefore support critical perspectives arguing that the effectiveness of educational digitalization depends not only on technological availability but also on broader educational ecosystems capable of supporting meaningful and equitable pedagogical transformation (Selwyn, 2022; Williamson et al., 2023).

3.2. Educational Benefits and Learning Opportunities Associated with Digital Technologies

The second major theme emerging from the analysis concerns the pedagogical benefits associated with digital technologies in biology education. Most participants perceived digital tools as important pedagogical resources capable of improving students' motivation, engagement, conceptual understanding, and inquiry-based learning experiences. Teachers consistently reported that digital technologies contribute to making biology lessons more dynamic, interactive, and attractive for students. Multimedia resources, scientific videos, and interactive animations were described as increasing students' interest and participation during classroom activities. Several participants explained that students demonstrate greater concentration and enthusiasm during digitally supported lessons compared to exclusively lecture-based teaching methods. These findings support recent research showing that digital learning environments may positively influence students' motivation and engagement in science education when technologies are integrated within active pedagogical approaches (Howard et al., 2024; Bond et al., 2021).

Table 3. Perceived Educational Benefits of Digital Technologies

Educational Benefit	Number	Percent
Increased Student Engagement	16	88.9
Improved Conceptual Understanding	15	83.3
Better Scientific Visualization	17	94.4
Enhanced Inquiry-Based Learning	13	72.2
Improved Collaborative Learning	12	66.7
Greater Access to Scientific Resources	14	77.8

Participants also emphasized that digital technologies improve students' conceptual understanding by facilitating the visualization of complex biological phenomena. Virtual simulations and interactive models allow students to observe scientific processes in detail and better understand relationships between biological concepts. According to several teachers, digital visualization tools are especially beneficial for students who experience difficulties understanding abstract scientific content through traditional verbal explanations alone. Digital animations illustrating cell division, DNA replication, ecological interactions, or physiological mechanisms were frequently mentioned as highly effective pedagogical supports for improving scientific comprehension. Classroom observations further confirmed that students appeared more capable of explaining biological processes after interacting with visual and interactive digital resources. The findings additionally indicate that digital technologies support inquiry-based learning practices in biology education. Teachers explained that online scientific resources, virtual experiments, and collaborative digital activities encourage students to ask questions, search for information independently, and participate more actively in scientific problem-solving processes. Several participants reported that digitally supported inquiry activities promote scientific curiosity and strengthen students' autonomy in knowledge construction. Rather than passively memorizing biological information, students were encouraged to investigate scientific phenomena, analyze experimental results, and discuss biological interpretations collaboratively. Classroom observations revealed that digitally supported activities often generated greater interaction and collaborative participation among students, particularly during group research tasks and virtual experimentation sessions.

Furthermore, teachers emphasized that digital technologies facilitate differentiated and personalized learning experiences. Participants explained that digital resources enable students to revisit lessons, pause educational videos, repeat simulations, and access supplementary explanations according to their individual learning pace and academic needs. Such flexibility appeared especially beneficial for students experiencing learning difficulties or requiring additional support to understand complex scientific concepts. Several teachers reported that weaker students often became more engaged and confident when visual and interactive technologies were integrated into classroom activities. These observations align with recent studies emphasizing the potential of digital learning environments to support inclusive and learner-centered pedagogical approaches (Redecker, 2023; UNESCO, 2023). Another important benefit identified by participants concerns the improvement of scientific visualization and experimental understanding. Biology teachers explained that many biological processes remain inaccessible to direct classroom observation because they occur at microscopic, molecular, or systemic levels. Virtual laboratories, simulations, and 3D animations therefore provided opportunities for students to visualize dynamic scientific processes that are difficult to observe through traditional teaching methods alone. Teachers noted that these technologies helped students better understand the relationships between theoretical scientific knowledge and observable biological phenomena. Several participants also indicated that digital technologies enhanced students' capacity to interpret scientific diagrams, analyze biological systems, and understand experimental procedures more effectively.

In addition, the findings reveal that digital technologies contribute to strengthening collaborative learning and communication processes in biology education. Through online educational platforms and digital communication tools, students were able to exchange information, work collaboratively on scientific tasks, and share educational resources outside classroom hours. Teachers explained that collaborative digital activities encouraged peer interaction, collective problem-solving, and cooperative learning dynamics. Some participants highlighted that shy or less academically confident students often participated more actively in digitally mediated collaborative environments than in traditional classroom discussions. Recent international research similarly suggests that digital collaborative learning environments may foster communication skills, social interaction, and cooperative scientific reasoning among learners (OECD, 2024; Williamson et al., 2023). Participants also highlighted that digital technologies facilitate access to updated scientific information beyond traditional textbooks. Through online platforms, educational websites, scientific databases, and multimedia resources, students are exposed to more diverse scientific materials and contemporary scientific knowledge. Teachers emphasized that access to updated digital content is particularly important in biology education because scientific discoveries and environmental issues evolve rapidly. Some participants explained that digital resources enabled teachers to connect biology lessons to current scientific debates related to ecology, public health, genetics, sustainability, and biotechnology. Such practices appeared to strengthen the relevance of biology education and promote stronger connections between scientific learning and real-world issues.

The analysis further demonstrates that digital technologies positively influence students' scientific reasoning and critical thinking skills when integrated within inquiry-oriented pedagogical practices. Several teachers reported that digitally supported activities encourage students to interpret scientific data, compare biological hypotheses, evaluate online scientific information, and engage in analytical discussions. Digital simulations and online scientific investigations appeared to support more exploratory and reflective learning processes compared to purely transmissive instructional methods. Participants explained that students increasingly develop analytical reasoning capacities when they actively manipulate digital resources and participate in problem-solving activities rather than simply receiving scientific information passively. However, despite these positive perceptions, several teachers emphasized that the pedagogical effectiveness of digital technologies largely depends on teachers' professional competencies, pedagogical adaptation strategies, and institutional conditions. Participants warned that technological tools alone do not automatically improve learning outcomes if they are not integrated within meaningful and student-centered pedagogical practices. Some teachers explained that poorly planned digital activities may lead to distraction, superficial learning, or excessive dependence on technological resources without improving scientific understanding. This observation aligns with recent literature stressing that successful educational digitalization depends on the interaction between technological resources, pedagogical quality, teacher professional development, and contextual adaptation (Tondeur et al., 2021; Williamson et al., 2023).

Moreover, the findings suggest that the educational benefits associated with digital technologies remain unevenly distributed across schools and educational contexts. Teachers working in schools with limited technological infrastructure often experienced difficulties implementing interactive pedagogical activities despite recognizing their educational value. In some rural or disadvantaged schools, insufficient internet access and limited digital equipment restricted students' opportunities to benefit fully from digitally enhanced learning experiences. These disparities illustrate that the pedagogical potential of digital technologies cannot be separated from broader socio-economic and institutional conditions shaping educational access and technological equity. Overall, the results demonstrate that digital technologies provide important pedagogical opportunities for improving biology education in Tunisian secondary schools. They contribute to enhancing students' engagement, scientific visualization, inquiry-based learning, collaborative participation, conceptual understanding, and access to scientific knowledge. Nevertheless, the educational effectiveness of these technologies remains closely dependent on teachers' professional competencies, pedagogical practices, institutional support mechanisms, and the reduction of infrastructural and socio-economic inequalities affecting digital access. These findings therefore support more critical and context-sensitive perspectives on educational digitalization by emphasizing that technological innovation alone cannot guarantee meaningful pedagogical transformation without adequate educational support systems and equitable learning conditions.

3.3. Institutional and Technological Challenges Affecting Digital Integration

Although participants generally recognized the educational value of digital technologies, the analysis revealed numerous institutional, technological, pedagogical, and socio-economic challenges affecting their effective integration into biology education. These constraints constitute one of the most significant dimensions emerging from the study because they directly influence teachers' capacity to implement innovative pedagogical practices and students' access to meaningful digital learning opportunities. The findings demonstrate that educational digitalization in Tunisian secondary schools remains strongly conditioned by structural inequalities, infrastructural limitations, and institutional disparities that shape everyday classroom realities. These constraints show that successful digital transformation also requires institutional and pedagogical support.

The most frequently mentioned challenge concerns insufficient technological infrastructure within secondary schools. Many participants reported limited access to computers, projectors, internet connectivity, interactive boards, printers, and digital laboratory equipment. Teachers working in rural schools described particularly difficult conditions characterized by unstable internet access, outdated technological resources, insufficient maintenance services, and limited institutional technological support. One participant explained that technical problems frequently prevent teachers from implementing digitally planned lessons effectively, often forcing them to abandon interactive activities and return to traditional teaching methods. Classroom observations confirmed that technological interruptions, equipment

malfunctions, and internet instability regularly disrupted pedagogical continuity during digitally supported lessons. The findings further reveal important disparities between schools located in urban and rural regions. Teachers working in urban schools generally reported better access to technological resources and institutional support, whereas participants from disadvantaged or remote regions described persistent infrastructural deficiencies limiting the effective implementation of digital pedagogies. In some rural schools, teachers indicated that a lack of multimedia classrooms and insufficient access to functional computers significantly restricted opportunities for integrating virtual laboratories, simulations, or online scientific resources into biology lessons. These disparities illustrate broader educational inequalities affecting the Tunisian educational system and support recent international research emphasizing that educational digitalization often reproduces existing socio-economic and territorial inequalities when institutional investment remains uneven (World Bank, 2024; Selwyn, 2022).

Table 4. Main Challenges Affecting Digital Technology Integration

Identified Challenge	Number	Percent
Insufficient Technological Infrastructure	16	88.9
Limited Professional Training	14	77.8
Unstable Internet Connectivity	13	72.2
Lack of Institutional Support	12	66.7
Students' Unequal Access to Technology	11	61.1
Increased Teacher Workload	10	55.6
Limited Access to Digital Laboratories	9	50.0

The analysis also indicates that insufficient professional training represents a major obstacle to sustainable digital integration. Several teachers reported receiving limited formal training concerning educational technologies, digital pedagogy, online learning environments, and inquiry-based digital teaching strategies (Schmid et al., 2024). Although national educational policies increasingly encourage ICT integration, participants explained that many teachers continue to feel insufficiently prepared to use advanced digital tools confidently and pedagogically effectively. Consequently, many participants relied primarily on self-training, peer collaboration, online tutorials, and personal experimentation to develop their digital competencies. Some teachers explained that they learned to use educational technologies progressively through informal professional networks rather than through structured institutional training programs. These findings suggest that digital integration requires not only technological equipment but also continuous professional development capable of strengthening teachers' pedagogical and technological competencies. Participants emphasized that many training initiatives remain overly technical and insufficiently focused on the pedagogical dimensions of digital education. Teachers expressed the need for more practical and context-sensitive professional development programs addressing classroom management, inquiry-based digital pedagogy, virtual experimentation, collaborative learning environments, and the adaptation of digital resources to students' diverse learning needs. Similar difficulties have been identified in recent international studies emphasizing that effective educational digitalization depends heavily on sustained teacher professional development and pedagogical support mechanisms (OECD, 2024; Trust & Whalen, 2021).

Another important issue concerns the discrepancy between institutional expectations regarding educational digitalization and the practical realities experienced in schools. While educational policies increasingly promote technological innovation and ICT integration as central dimensions of educational reform, participants emphasized that schools often lack the financial resources, technical maintenance services, pedagogical support structures, and institutional coordination necessary for sustainable implementation. Several teachers expressed frustration regarding what they perceived as unrealistic institutional expectations disconnected from the material realities of classrooms. Participants explained that educational authorities frequently encourage the use of digital technologies without adequately addressing infrastructural constraints, internet instability, overcrowded classrooms, and unequal technological access among students. Classroom observations further confirmed that technological difficulties frequently interrupted pedagogical activities and limited the effectiveness of digitally supported lessons. In some cases, teachers spent considerable instructional time solving technical problems, reconnecting internet access, or adapting lessons because digital equipment was unavailable or malfunctioning. Such disruptions often reduced opportunities for inquiry-based activities, collaborative experimentation, and interactive learning

processes. Some participants reported feeling discouraged from using advanced digital pedagogies because of recurrent technical uncertainties and the absence of immediate institutional assistance when problems emerged.

The findings additionally demonstrate that socio-economic inequalities significantly influence students' access to digital learning opportunities. Several teachers explained that many students lack personal computers, stable internet access, tablets, or smartphones at home, particularly in disadvantaged regions and low-income households. These inequalities became especially visible during periods of online learning following the COVID-19 pandemic, when numerous students experienced difficulties participating regularly in remote educational activities. Participants reported that some students were unable to access digital assignments, online educational platforms, or virtual classes because of limited technological resources within their families. Teachers emphasized that such inequalities negatively affect educational continuity and contribute to widening learning gaps between students from different socio-economic backgrounds. Furthermore, several participants expressed concern that digital transformation processes may unintentionally reinforce pre-existing educational inequalities if institutional support remains insufficient. Teachers noted that students with stronger technological access and greater digital familiarity often benefit more significantly from digitally enhanced learning environments than students facing technological exclusion. Recent literature similarly highlights that educational digitalization may deepen inequalities related to access, participation, and academic achievement when equitable support mechanisms are absent (UNESCO, 2023; Williamson et al., 2023). Consequently, participants argued that educational policies should address not only technological modernization but also broader issues of digital equity and social inclusion.

Another significant challenge identified by participants concerns the increased professional workload associated with digital integration. Teachers explained that preparing digitally supported lessons requires substantial additional time and effort. Searching for scientific videos, selecting reliable online resources, adapting pedagogical materials, designing interactive activities, managing online platforms, and solving technical problems considerably increase teachers' professional responsibilities. Several participants reported spending many additional hours outside regular teaching schedules preparing digital resources and adapting lessons to technological constraints. Some teachers expressed concern regarding the absence of sufficient institutional recognition and pedagogical support for these additional professional demands. The analysis also suggests that the rapid evolution of educational technologies creates continuous pressure on teachers to update their digital competencies and adapt to changing pedagogical expectations. Participants explained that technological innovation evolves faster than institutional training opportunities, creating professional uncertainty and feelings of inadequacy among some teachers. Older teachers in particular sometimes reported difficulties adapting to rapidly changing digital environments and integrating advanced technological tools into their established pedagogical practices. Nevertheless, many participants demonstrated strong professional resilience and adaptive capacity by developing informal learning strategies, collaborative support networks, and contextually adapted pedagogical solutions. In addition, limited access to digital laboratories and scientific simulation software represented another important obstacle affecting biology education specifically. Several participants explained that biology teaching often requires experimentation, observation, and scientific visualization tools that remain unavailable in many schools. While virtual laboratories may partially compensate for insufficient physical laboratory resources, their implementation depends on technological infrastructure that many schools still lack. Consequently, some teachers remained restricted to theoretical explanations and simplified visual presentations rather than more interactive forms of scientific experimentation and inquiry-based learning.

The findings therefore reveal that the integration of digital technologies in biology education is shaped by complex interactions between institutional conditions, infrastructural realities, socio-economic inequalities, pedagogical competencies, and professional adaptation strategies. Although teachers generally recognized the educational potential of digital technologies, their effective implementation remains constrained by structural limitations that extend beyond individual pedagogical motivation or technological availability alone. These results support critical perspectives arguing that educational digitalization should be understood as a socio-pedagogical and institutional transformation process rather than merely a technical modernization initiative (Selwyn, 2022). Overall, the study demonstrates that sustainable and equitable digital integration in biology education requires comprehensive educational policies capable of addressing infrastructural inequalities, strengthening teacher professional development, improving institutional

support systems, and reducing disparities in students' access to technological resources. Without such structural support mechanisms, the pedagogical benefits associated with digital technologies risk remaining unevenly distributed across schools and social groups. Consequently, educational digitalization in Tunisia must be accompanied by broader strategies promoting educational equity, institutional investment, and context-sensitive pedagogical innovation in order to ensure meaningful and inclusive digital transformation within biology education.

4. DISCUSSION

The present study explored the integration of digital technologies in biology education within Tunisian secondary schools and highlighted both the pedagogical opportunities and the structural constraints associated with educational digitalization. The findings indicate that digital technologies contribute to improving students' engagement, scientific visualization, conceptual understanding, collaborative learning, and inquiry-based learning experiences. At the same time, the study demonstrates that the effectiveness of digital integration remains strongly dependent on institutional support, technological infrastructure, teachers' professional competencies, and socio-economic conditions (Konstantinidou & Scherer, 2022). This finding is consistent with recent international research emphasizing that the educational value of technology depends less on the mere availability of digital tools than on how they are pedagogically integrated and supported by appropriate institutional conditions (Sailer & Homner, 2020; Tondeur et al., 2021; UNESCO, 2023). Educational digitalization should therefore not be understood solely as a process of technical modernization but rather as a complex pedagogical and socio-institutional transformation shaped by contextual realities, educational inequalities, teacher competencies, and local adaptation strategies (Selwyn, 2022; UNESCO, 2023; OECD, 2024). This interpretation is particularly relevant in the Tunisian context, where technological development takes place alongside persistent differences in infrastructure, institutional resources, and teachers' access to professional development.

One of the principal findings of this research concerns the increasing use of digital technologies by biology teachers to facilitate the teaching of complex scientific concepts. Participants reported that multimedia presentations, scientific videos, simulations, online resources, interactive platforms, and virtual laboratories supported students' understanding of abstract biological processes such as genetics, molecular interactions, cellular division, ecological systems, and human physiology. These findings are consistent with previous studies showing that digital visualization and simulation tools can facilitate conceptual understanding by providing learners with dynamic and interactive representations of phenomena that are difficult to observe directly (Ibáñez & Delgado-Kloos, 2018; Sailer & Homner, 2020; Howard et al., 2024). Research on technology-supported science learning similarly suggests that simulations and visual representations can help learners establish connections between theoretical explanations and observable or manipulable representations of scientific phenomena (Chiu et al., 2023). Biology education may particularly benefit from such technologies because many biological processes occur at microscopic, molecular, temporal, or spatial scales that cannot be directly observed in conventional classroom settings. Digital representations can consequently make invisible or dynamic phenomena more accessible to learners and support the construction of explanatory models (Ibáñez & Delgado-Kloos, 2018; Chiu et al., 2023). However, the literature also indicates that visualization alone does not automatically produce conceptual understanding; its effectiveness depends on instructional guidance, the cognitive demands of the activity, and the extent to which students are encouraged to interpret rather than merely observe digital representations (Sailer & Homner, 2020). The present findings therefore suggest that the pedagogical contribution of digital technologies lies primarily in their capacity to mediate scientific concepts within appropriately designed learning activities.

The results also demonstrate that digital technologies positively influence students' motivation, classroom participation, and collaborative engagement. Teachers observed that digitally supported lessons generated greater student attention, curiosity, interaction, and participation than exclusively lecture-based approaches. These observations are broadly consistent with research showing that technology-supported active learning can increase behavioural and cognitive engagement when digital tools are integrated into learner-centred instructional designs (Bond et al., 2021; Sailer & Homner, 2020; Howard et al., 2024). In the present study, digital technologies not only diversified teaching methods but also created opportunities for students to participate more actively in scientific inquiry and collaborative problem-solving activities.

Classroom observations further revealed that students appeared more motivated when lessons included visual simulations, educational videos, and interactive scientific content. This finding can be interpreted in light of research suggesting that interactive technologies may support student engagement by increasing opportunities for participation, feedback, collaboration, and active manipulation of learning materials (Bond et al., 2021). Nevertheless, the literature cautions against equating the presence of technology with improved motivation or learning outcomes (Sailer et al., 2021). The educational benefits of digital environments are influenced by task design, teacher mediation, learner characteristics, and the degree of cognitive involvement required from students (Sailer & Homner, 2020; UNESCO, 2023). Accordingly, the present findings reinforce the importance of integrating technology within pedagogical approaches that promote interaction, exploration, collaboration, and critical thinking rather than using digital resources merely as substitutes for traditional teacher-centred instruction.

Furthermore, the study highlights the important role of digital technologies in supporting inquiry-based learning and scientific reasoning in biology education. Participants explained that online scientific resources, virtual experimentation, collaborative digital activities, and interactive educational platforms encouraged students to search for information independently, formulate scientific questions, analyse biological phenomena, and engage in reflective reasoning processes. These findings are consistent with research indicating that technology can support inquiry-oriented science learning by providing learners with opportunities to access information, manipulate representations, conduct simulations, communicate findings, and receive feedback (Tondeur et al., 2021; UNESCO, 2023). Digital technologies may therefore create conditions favourable to the development of higher-order cognitive processes, including critical thinking, scientific interpretation, collaborative problem-solving, and autonomous learning, particularly when learners are required to actively process and evaluate digital information rather than simply consume it. This interpretation is also compatible with constructivist and socio-constructivist perspectives, according to which meaningful learning develops through active engagement, interaction, and contextualized knowledge construction (Barron & Darling-Hammond, 2010). However, the present findings should not be interpreted as evidence that technology itself produces inquiry-based learning. Rather, they suggest that digital tools can provide affordances for inquiry when teachers deliberately integrate them into pedagogically structured activities. This distinction is important because previous research has shown that technology integration remains dependent on teachers' instructional decisions and professional competencies (Tondeur et al., 2021; Redecker, 2023).

Another important finding concerns teachers' adaptive pedagogical practices in response to institutional and technological limitations. Despite infrastructural difficulties, many participants demonstrated considerable professional creativity and resilience by developing alternative pedagogical strategies adapted to local realities. Teachers frequently combined traditional teaching methods with accessible digital resources to compensate for insufficient technological infrastructure. Several participants explained that they downloaded educational videos in advance, used personal digital devices, or relied on free online scientific resources to maintain digitally supported instruction despite unstable internet connectivity. These practices illustrate that technology integration is not simply a matter of implementing institutional prescriptions but also involves teachers' professional judgement, adaptation, and agency. This interpretation is supported by research conceptualizing teacher agency as an important factor in professional learning, school improvement, and sustainable educational change (Ngo, 2022). Similarly, studies of teachers' professional digital competence emphasize that effective technology integration requires the capacity to select, adapt, evaluate, and pedagogically use digital resources rather than merely possess technical skills (Redecker, 2017; Scherer et al., 2022). The adaptive practices observed in the present study therefore suggest that Tunisian biology teachers actively negotiate the relationship between available technologies and classroom requirements. Their use of personal resources and offline materials can be understood as a form of contextual adaptation that allows teachers to preserve pedagogical continuity under infrastructural constraints (Scherer et al., 2018). At the same time, such individual adaptation should not replace institutional responsibility for providing adequate technological and pedagogical support.

However, the study also reveals that the pedagogical effectiveness of digital technologies remains uneven and highly dependent on contextual conditions. One of the most significant findings concerns the persistence of infrastructural and socio-economic inequalities affecting digital integration in Tunisian secondary schools. Teachers working in rural or disadvantaged regions frequently reported insufficient internet connectivity, outdated technological equipment, overcrowded classrooms, and limited institutional

support. These disparities restricted opportunities for implementing advanced digital pedagogies such as virtual laboratories, inquiry-based digital experimentation, collaborative online learning, and scientific simulations. Similar patterns have been documented internationally, with research showing that unequal access to devices, connectivity, digital resources, and appropriate support can reproduce or intensify existing educational inequalities (Selwyn, 2022; World Bank, 2024; UNESCO, 2023). The UNESCO Global Education Monitoring Report particularly emphasizes that technology can contribute to educational inclusion only when issues of access, equity, relevance, sustainability, and teacher capacity are addressed simultaneously (UNESCO, 2023). Consequently, the present findings demonstrate that digital transformation in education cannot be separated from broader questions of educational justice, social inclusion, and equitable access to learning opportunities (Redecker, 2023). The results also suggest that the digital divide should be understood not only as a problem of access to devices or connectivity but also as a problem of the conditions under which students and teachers can meaningfully use digital technologies for learning.

The findings additionally demonstrate that insufficient professional training represents a major challenge affecting sustainable digital integration. Several teachers explained that they had received limited formal preparation concerning digital pedagogy, online learning environments, educational technologies, and inquiry-based digital teaching strategies. Consequently, many participants relied primarily on self-training, peer collaboration, informal experimentation, and online tutorials to develop their digital competencies. These findings are consistent with research emphasizing that teachers' digital competence encompasses more than basic technical knowledge and includes the pedagogical ability to select and integrate digital resources appropriately into teaching and learning processes (Howard et al., 2021; Redecker, 2017; Scherer et al., 2022). A systematic review of professional digital competence similarly highlights the importance of teachers' knowledge and skills in selecting and using digital resources for pedagogical purposes (Schmid et al., 2022). Recent research further indicates that professional development can influence teachers' digital instructional practices, particularly when training is sustained, practical, pedagogically oriented, and connected to classroom needs (Amemasor et al., 2025). The present study therefore supports the view that continuous professional development constitutes a central condition for sustainable educational digitalization. Importantly, training should not be limited to learning how to operate technological tools. It should also address instructional design, digital resource evaluation, inquiry-based learning, collaborative learning, assessment, and the critical use of technology. The present study further suggests that teachers' professional agency and adaptive capacity play an important role in technology integration, particularly in contexts characterized by limited institutional support (Ngo, 2022).

Another important finding concerns the tensions between institutional discourses promoting educational digitalization and the practical realities experienced within schools. Although educational policies increasingly encourage ICT integration and technological modernization, participants emphasized that schools frequently lack sufficient financial resources, maintenance services, technical assistance, and pedagogical support mechanisms necessary for sustainable implementation. These findings support critical perspectives on educational digitalization that challenge the assumption that technological innovation automatically improves educational quality (Selwyn, 2022; Williamson et al., 2023). The UNESCO (2023) report similarly stresses that technology should be judged according to its educational relevance, equity, sustainability, and capacity to support rather than replace human interaction. The results therefore challenge technologically deterministic approaches that present digitalization as a universal solution to educational problems independently of contextual realities. Instead, they suggest that the educational impact of digital technologies depends on the interaction between technological resources, institutional conditions, teachers' professional competencies, pedagogical practices, and students' learning contexts. In the Tunisian case, the gap between policy ambitions and classroom realities appears particularly important because teachers may be encouraged to integrate digital technologies without always receiving the infrastructure, maintenance, training, or pedagogical support necessary to translate these policy expectations into sustainable classroom practices.

The study also demonstrates that socio-economic inequalities significantly influence students' access to digital learning opportunities. Several teachers explained that many students, particularly in disadvantaged regions, lack personal computers, stable internet access, tablets, or smartphones at home. These inequalities became especially visible during periods of online learning following the COVID-19 pandemic. Participants reported that some students experienced serious difficulties participating in remote learning activities

because of technological exclusion and limited digital resources within their families. Such findings are consistent with international evidence showing that the transition to remote learning during the COVID-19 pandemic exposed substantial inequalities in access to devices, connectivity, digital skills, and appropriate learning environments (Dhawan, 2020; UNESCO, 2023). The UNESCO report further emphasizes that technology can either reduce or reproduce inequalities depending on how access and support are organized. Consequently, educational digitalization may unintentionally reinforce pre-existing inequalities if public policies fail to ensure equitable access to technological resources and inclusive digital learning environments. The present findings therefore extend the discussion of the digital divide beyond technological access alone: students' ability to benefit from digital learning also depends on household resources, parental support, learning conditions, and digital competencies. This multidimensional understanding of digital inequality is important when interpreting technology integration in contexts where socio-economic disparities may affect students' opportunities to engage with digital learning outside school.

From a theoretical perspective, this study contributes to the growing literature on digital education and science education by providing empirical evidence from a North African and Global South context that remains comparatively underrepresented in international research. Much of the literature on educational technologies has been generated in European, North American, and other relatively well-resourced educational systems. The present research highlights the importance of contextual realities, institutional inequalities, and adaptive pedagogical practices in shaping technology integration within Tunisian secondary biology education. This finding is consistent with critical approaches that call for greater attention to the social, political, institutional, and cultural contexts in which educational technologies are introduced (Selwyn, 2022; UNESCO, 2023). The study therefore supports a more context-sensitive conceptualization of digital transformation in which pedagogy, infrastructure, institutional support, teacher agency, socio-economic conditions, and local educational priorities are considered as interconnected dimensions rather than isolated variables. In this respect, the Tunisian case demonstrates that teachers' creative adaptation of digital resources can coexist with significant structural constraints. The contribution of the study consequently lies not in demonstrating that digital technologies are universally beneficial, but in showing how their educational value is negotiated within specific institutional and socio-economic conditions.

From a practical perspective, the findings have important implications for educational policy and teacher professional development in Tunisia. First, the study demonstrates the necessity of strengthening technological infrastructure in secondary schools, particularly in rural and socio-economically disadvantaged regions. Improving internet connectivity, access to digital equipment, maintenance services, and technological support systems appears essential for ensuring more equitable digital learning opportunities. Such investments should be accompanied by mechanisms for monitoring actual use and ensuring the long-term sustainability of technological provision, since the availability of equipment alone does not guarantee meaningful educational integration (UNESCO, 2023). Second, the findings highlight the importance of continuous professional development programmes focused not only on technical skills but also on digital pedagogy, inquiry-based learning, collaborative teaching strategies, assessment, and the pedagogical integration of scientific simulations and multimedia resources. Evidence from research on teacher digital competence indicates that professional learning should enable teachers to make informed pedagogical choices concerning the selection, adaptation, and evaluation of digital resources (Schmid et al., 2022; Amemasor et al., 2025). Teachers therefore require sustained institutional support in order to integrate digital technologies meaningfully, critically, and contextually into biology education practices. Moreover, the study suggests that educational digitalization policies should be adapted to local educational realities rather than based exclusively on standardized technological modernization models. Context-sensitive approaches that consider institutional disparities, teachers' professional experiences, students' socio-economic conditions, and regional inequalities are essential for developing sustainable and inclusive digital education strategies. This position is consistent with the UNESCO (2023) emphasis on equity, relevance, sustainability, and context in technology-related educational policies.

Greater collaboration between policymakers, educational institutions, teachers, and local communities may also contribute to improving the implementation of educational technologies in secondary schools and reducing digital inequalities affecting students' learning opportunities. Such collaboration could include teacher participation in technology planning, locally adapted professional development, technical support mechanisms, and systematic evaluation of the pedagogical use of digital

resources. These measures would help shift digitalization from a predominantly equipment-centred approach toward a more sustainable model centred on pedagogical needs and educational equity. Finally, although this study provides important insights into digital integration in Tunisian biology education, certain limitations should be acknowledged. The qualitative design and relatively limited sample size do not allow statistical generalization to all Tunisian secondary schools. Future research could therefore combine qualitative and quantitative approaches in order to examine digital pedagogical practices across larger educational populations and compare regional variations more systematically. Additional studies could also explore students' perspectives regarding digital learning experiences and investigate the longer-term relationship between digital technologies and scientific achievement, critical thinking, environmental awareness, and educational equity in biology education. Future research should also examine whether particular types of digital tools, such as simulations, virtual laboratories, collaborative platforms, or augmented reality, produce different learning effects under different pedagogical and infrastructural conditions. Comparative studies involving other North African or Global South educational systems could additionally contribute to a broader understanding of how contextual realities shape educational digitalization processes internationally.

Overall, the findings demonstrate that digital technologies provide important pedagogical opportunities for improving biology education in Tunisia, particularly in relation to scientific visualization, inquiry-based learning, collaborative interaction, and students' engagement. Nevertheless, these benefits should not be interpreted as inherent properties of technology itself. Rather, they emerge from the interaction between digital affordances, teacher mediation, pedagogical design, institutional support, and students' learning conditions (Sailer & Homner, 2020; Tondeur et al., 2021; UNESCO, 2023). The success of educational digitalization therefore depends not only on technological availability but also on sustained institutional investment, teacher professional development, equitable access to digital resources, teacher agency, pedagogical innovation, and contextually adapted educational policies. In the Tunisian context, meaningful digital transformation consequently requires a shift from technology-centred modernization toward a pedagogically grounded and socially equitable approach capable of supporting sustainable and inclusive transformation in biology education.

5. CONCLUSION

This study examined the integration of digital technologies in biology education within Tunisian secondary schools, with particular attention to the pedagogical opportunities and structural challenges associated with educational digitalization. The findings demonstrate that digital technologies play an increasingly important role in transforming biology teaching practices by improving scientific visualization, facilitating conceptual understanding, supporting inquiry-based learning, and increasing students' engagement and participation. Multimedia resources, virtual simulations, online scientific platforms, and interactive educational tools were perceived by teachers as valuable pedagogical instruments capable of making biology learning more dynamic, accessible, and student-centered. These findings are consistent with recent studies emphasizing that educational technologies may significantly improve science learning when integrated into active and inquiry-oriented pedagogical approaches (Bond et al., 2021; Howard et al., 2024). The study therefore confirms that digital technologies may contribute to the modernization of science education and to the development of more interactive and collaborative learning environments (OECD, 2024). However, the research also highlights that the effectiveness of digital integration remains strongly influenced by institutional conditions, technological infrastructure, teachers' professional preparation, and socio-economic inequalities affecting schools and students. The findings reveal that insufficient internet connectivity, limited access to digital equipment, inadequate professional training, and disparities between urban and rural schools continue to restrict the implementation of sustainable and equitable digital pedagogical practices. Similar conclusions have been identified in recent international research demonstrating that digital transformation processes frequently reproduce existing educational inequalities when institutional support remains insufficient (Selwyn, 2022; UNESCO, 2023). Consequently, the study demonstrates that educational digitalization cannot be reduced to the simple introduction of technological tools into classrooms.

Rather, it represents a broader pedagogical, institutional, and social transformation requiring continuous support, contextual adaptation, and long-term educational investment (Williamson et al., 2023).

Another important contribution of this research concerns the role of teachers as central actors in educational digitalization processes. Despite numerous institutional and infrastructural constraints, many biology teachers developed adaptive strategies and innovative pedagogical practices in order to integrate digital technologies into their teaching. These findings illustrate the importance of teachers' professional agency, creativity, and pedagogical flexibility in supporting meaningful educational innovation. Similar observations have been reported by Tondeur et al. (2021), who emphasize that successful technology integration depends largely on teachers' competencies, pedagogical adaptation, and institutional support systems. The present study therefore suggests that successful digital transformation depends not only on technological availability but also on teachers' professional development and pedagogical conditions capable of fostering inclusive and student-centered learning environments. From a theoretical perspective, this research contributes to the growing literature on digital education and science education by providing empirical evidence from the Tunisian and North African educational context, which remains relatively underrepresented in international research. The study highlights the importance of adopting context-sensitive approaches to educational digitalization that consider institutional inequalities, socio-economic disparities, and local pedagogical realities. In doing so, it challenges technologically deterministic perspectives that present digital transformation as a universally applicable educational solution independent of contextual conditions (Selwyn, 2022; Trucano, 2016). The findings further support recent critical discussions emphasizing that digital innovation should be analyzed through broader questions related to educational equity, social inclusion, and sustainable pedagogical development (UNESCO, 2023; OECD, 2024).

From a practical perspective, the findings have important implications for the different stakeholders involved in the digital transformation of biology education. For educators, the results highlight the need to move beyond the simple use of digital tools as technological substitutes for conventional teaching and to integrate them purposefully into inquiry-based, collaborative, problem-solving, and student-centered learning activities. Teachers should be encouraged to select digital resources according to clearly defined pedagogical objectives and to use simulations, scientific videos, virtual laboratories, interactive platforms, and online resources when these tools provide added educational value. Professional development should therefore go beyond basic technical training and address the pedagogical design of technology-enhanced learning, the critical evaluation of online scientific information, digital assessment, classroom management in technology-supported environments, and the adaptation of digital resources to students' different levels of digital competence. In the Tunisian context, teacher training should also prepare educators to work effectively under conditions of limited connectivity and technological resources by developing strategies such as offline access to digital materials, the use of lightweight applications, and the integration of students' available digital devices where pedagogically appropriate. Such an approach would strengthen teachers' professional agency while reducing dependence on technological conditions that may not always be available in schools.

For curriculum developers, the findings suggest that digital education should be incorporated systematically into biology curricula rather than treated as an additional or optional component. Curriculum development should establish explicit links between digital competencies, scientific competencies, inquiry-based learning, and disciplinary knowledge. Digital activities should be aligned with learning objectives, classroom practices, and assessment procedures so that technology contributes directly to the development of scientific reasoning rather than simply increasing the quantity of digital content available to students. Biology curricula could, for example, provide opportunities for students to interpret simulations, analyse digital scientific data, construct and evaluate biological models, conduct virtual experiments, compare scientific information from different digital sources, and communicate evidence-based explanations using digital media. Such integration should nevertheless remain sensitive to the Tunisian curriculum, the realities of secondary schools, teachers' workload, and differences in technological provision between regions. Curriculum developers should therefore avoid technology-dependent activities that cannot be implemented equitably across schools and should provide alternative low-tech or offline pathways when necessary.

For educational policymakers, the findings underline the necessity of adopting a comprehensive digitalization strategy that addresses infrastructure, teacher preparation, educational equity, technical support, and long-term sustainability simultaneously. Improving internet connectivity and providing adequate digital equipment remain essential, particularly in rural and socio-economically disadvantaged schools; however, investment should also include equipment maintenance, replacement mechanisms,

technical assistance, cybersecurity, access to appropriate educational platforms, and reliable electricity and connectivity. Policymakers should also consider regional disparities when allocating resources rather than relying on uniform technological provision. Targeted funding mechanisms could help schools facing greater infrastructural and socio-economic constraints to achieve minimum conditions for meaningful digital learning. Furthermore, educational policies should establish mechanisms for monitoring not only the distribution of technological equipment but also its actual pedagogical use and educational impact. This would help shift digitalization policies from an equipment-centred model toward a more sustainable and pedagogically oriented approach. In accordance with international recommendations, technology-related policies should place educational equity, accessibility, relevance, sustainability, and teacher support at the centre of digital transformation (UNESCO, 2023; OECD, 2024).

For school administrators, the findings indicate that effective digital integration requires supportive school-level conditions rather than relying exclusively on individual teachers' motivation and initiative. Administrators should ensure that available equipment is functional, accessible, and appropriately maintained and that teachers have access to technical assistance when technological problems occur. Schools could also establish professional learning communities in which teachers exchange experiences, demonstrate successful digital practices, develop shared resources, and collectively address technological and pedagogical difficulties. School administrators can further support digital integration by allocating time for collaborative planning, encouraging experimentation with appropriate technologies, coordinating access to digital facilities, and identifying teachers' professional development needs. In resource-constrained settings, administrators may also play an important role in developing locally appropriate solutions, such as shared digital resources, offline repositories, coordinated use of available devices, and partnerships with local educational institutions. Such organizational support can reduce the burden placed on individual teachers and contribute to a more sustainable culture of digital innovation within schools.

For researchers, the findings open several directions for future investigation. Further research should examine digital technology integration across larger and more diverse samples of Tunisian schools in order to identify regional, institutional, and socio-economic variations more systematically. Mixed-methods and longitudinal studies would be particularly valuable for examining not only teachers' perceptions and reported practices but also students' actual learning outcomes, engagement, digital competencies, scientific reasoning, and long-term academic development. Future studies could also compare different types of digital technologies, such as simulations, virtual laboratories, augmented reality, learning management systems, and collaborative platforms, in order to determine which technological affordances are most beneficial for particular biology concepts and learning objectives. Greater attention should also be given to students' experiences, including their access to technologies outside school, their digital literacy, their capacity to evaluate online scientific information, and the ways in which socio-economic conditions influence their ability to benefit from technology-supported learning. Comparative research involving Tunisia and other North African or Global South educational systems could further clarify how cultural, institutional, infrastructural, and policy contexts influence the implementation and educational value of digital technologies.

Finally, for educational technology designers and developers, the findings emphasize the importance of designing digital resources that are pedagogically meaningful, technically accessible, affordable, and adaptable to diverse educational contexts. In settings where internet connectivity and technological infrastructure remain uneven, educational platforms and biology applications should incorporate low-bandwidth functionality, offline access, downloadable resources, compatibility with commonly available devices, and interfaces that remain usable under limited technical conditions. Digital biology resources should also be designed around authentic pedagogical needs rather than technological novelty. In particular, they should facilitate scientific visualization, modelling, inquiry, experimentation, collaboration, formative feedback, and the interpretation of scientific data. Designers should provide teachers with sufficient flexibility to modify activities, adjust levels of difficulty, select appropriate content, and integrate digital resources with existing curricular materials. Accessibility should also be considered so that digital resources can be used by students with different learning needs and levels of digital competence. Collaboration among technology designers, biology teachers, curriculum specialists, researchers, and students would further contribute to the development of resources that are pedagogically relevant and contextually appropriate.

Taken together, these implications indicate that sustainable educational digitalization cannot be achieved through isolated interventions or through technological investment alone. It requires coordinated

action across the educational ecosystem, in which teachers provide pedagogical mediation, curriculum developers ensure curricular coherence, policymakers establish equitable structural conditions, school administrators create supportive organizational environments, researchers generate evidence for decision-making, and technology designers develop accessible and context-sensitive tools. Such coordination is particularly important in the Tunisian context, where differences in infrastructure, regional resources, teacher preparation, and students' socio-economic conditions may influence the extent to which digital technologies translate into meaningful educational opportunities. The findings therefore support a holistic approach to digital transformation in which technological innovation is considered a means of improving the quality, inclusiveness, and relevance of biology education rather than an objective in itself (Selwyn, 2022; UNESCO, 2023; OECD, 2024).

Nevertheless, certain limitations should be acknowledged. The qualitative nature of the study and the relatively limited number of participants do not allow statistical generalization to all Tunisian secondary schools. In addition, the study focused primarily on teachers' perceptions and classroom practices without extensively examining students' perspectives or quantitative learning outcomes. Future research could therefore combine qualitative and quantitative methodologies in order to analyze digital learning practices across larger educational populations and explore the long-term impact of digital technologies on students' scientific achievement, critical thinking, motivation, and educational equity. Comparative studies involving other educational systems in North Africa and the Global South may also contribute to a broader understanding of how contextual realities shape digital transformation in science education (World Bank, 2024). Overall, this study demonstrates that digital technologies offer important opportunities for improving biology education in Tunisia by promoting more interactive, visual, and inquiry-oriented learning experiences. Nevertheless, achieving meaningful and sustainable educational digitalization requires more than technological modernization alone. It requires equitable educational policies, institutional commitment, continuous teacher support, context-sensitive curricula, appropriate technology design, and collaboration among the different stakeholders involved in educational transformation. When these conditions are addressed simultaneously, digital technologies can contribute not only to educational quality but also to greater inclusion, participation, and social equity within contemporary science education systems (UNESCO, 2023; Williamson et al., 2023).

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Research Ethics. This study was conducted in accordance with the applicable national educational regulations and institutional ethical standards governing research involving human participants. Prior to data collection, all participants were informed about the objectives and procedures of the study, the voluntary nature of their participation, confidentiality measures, and their right to withdraw from the study at any time without consequences. Informed consent was obtained from all participants before interviews and classroom observations were conducted. The research protocol was conducted with the authorization of the relevant educational and institutional authorities responsible for supervising research activities in Tunisia. All data were anonymized and used exclusively for academic and scientific purposes.

Data Availability Statement. The data supporting the findings of this study are available from the corresponding author upon reasonable request. Due to ethical considerations and confidentiality agreements with participants and participating educational institutions, the complete dataset is not publicly available. Anonymized interview excerpts and relevant research materials may be made available for academic purposes, subject to applicable ethical and institutional requirements.

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