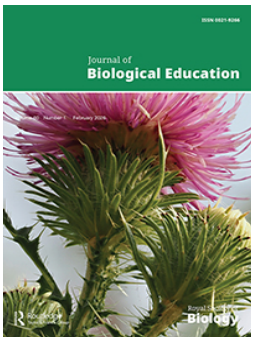

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REVIEW ARTICLE

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Beyond ChatGPT: a review of the use of AI tools in biological education

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ABSTRACT
Artificial intelligence (AI) is increasingly shaping biological research, yet its adoption within biological education has been much slower, partly due to concerns surrounding generative AI (GAI) tools such as ChatGPT. Despite this, AI-driven applications including iNaturalist and Google Lens are being used to support teaching and learning in biology. This review examines the potential benefits of AI in biological education, including enhanced student engagement and subject knowledge, support for coding skills, assistive technologies for students with disabilities, and the use of predictive modelling to identify at-risk students. It also reviews emerging literature on the integration of specialised machine learning tools for bioimaging and species identification in biology teaching. Evidence suggests that tools such as iNaturalist can improve learning outcomes, promote engagement, and foster environmental stewardship. However, challenges associated with GAI are also discussed, including academic integrity, assessment design, misinformation, and the potential erosion of critical thinking and independent research skills. To maximise benefits while minimising risks, appropriate professional development for educators and clear guidance for students are essential. The review highlights the need for further rigorous research, particularly regarding impacts on critical thinking and the integration of AI into laboratory and field-based activities.

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Artificial intelligence; Biological education; Generative AI; Machine learning; Educational technology

Introduction

It is no understatement to say that Artificial Intelligence (AI) has revolutionised biology research; most clearly illustrated by the award of the Nobel Prize to the Google DeepMind scientists who developed the Alpha Fold model to predict protein structures (Callaway 2024). In under a decade, AI has transformed 'omics (Szalata et al. 2024), molecular and cellular engineering (Abudayyeh and Gootenberg 2024), and shows great potential in fields as disparate as cancer biology (Fan, Nazaret, and Azizi 2024), animal behaviour (Goodwin et al. 2024) and tackling the biodiversity crisis (Han et al. 2023). All these developments underpin biological education – at least at the tertiary level – thus consideration of AI in this context is an urgent imperative.

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Prior to 2022 the use of AI was rare, even among scientists, as it required high-level programming skills. This changed almost overnight with OpenAI's ChatGPT, a chatbot using Generative AI (GAI) that was easy to use and freely available. ChatGPT is a large language model (LLM), just one of a range of deep learning models, trained on a huge data-set and able to generate human-sounding text (See Table S1 for a Glossary of terms used in Artificial Intelligence). In 2023, ChatGPT was included alongside human researchers in Nature's list of the biggest stories in science (Kramer 2023). Alongside ChatGPT came growth in other AI applications, including computer vision models that identify species from images (e.g. i-Naturalist). These systems use neural networks trained on vast collections of labelled images and can be used to support learning and engagement especially through fieldwork.

Almost as soon as ChatGPT was released in 2022, it provoked controversy, both for its potential impact on educational outcomes and for the environmental damage caused by its use. Within months it was blocked in China and Italy, sued for defamation of character, investigated by the US Federal Trade Commission, and banned in universities across the globe (Sullivan, Kelly, and McLaughlan 2023). One of the major educational concerns has been the challenge to assessment integrity (Cotton, Cotton, and Shipway 2023); many traditional forms of university assessment were easily completed using GAI tools, and this has become a more pressing issue as tools are updated. While they remain only 'stochastic parrots' (Bender et al. 2021), increases in the size of the training sets and underlying computing power have dramatically increased their scope and accuracy. OpenAI claim that GPT-4 ranked in the 99th percentile of students competing in the Biology Olympiad (Koetsier 2023), and essays generated entirely by GPT-4 achieved higher grades than undergraduates at the University of Reading where the AI writing went almost entirely undetected (Scarfe et al. 2024). Though the initial panic has largely subsided, universities are still unsure how to manage GAI. While some consider GAI to represent the future of teaching and learning, others perceive it as a threat to students developing core skills such as problem-solving (Baidoo-Anu and Owusu Ansah 2023; Yu 2023). It is clear from surveys of thousands of undergraduate students in Sweden (Stöhr, Wanyu Ou, and Malmström 2024) and the UK (Freeman 2024) that the use of GAI is extensive, with around 16% of students admitting using it in assessments.

Previous reviews have considered the geographical spread of research on AI in education, the focus of studies, and gaps in the literature. Chen, Chen, and Lin (2020) draw largely positive conclusions from their review, focusing on the benefits of AI for teaching, personalised learning, and more efficient marking. But this review already seems to reflect a different era for AI in education, pre-dating ChatGPT and the subsequent explosion of research fuelled by concerns about student cheating. Zhai et al. (2021) also review literature on AI and education pre-2020 but take a more critical stance, foreseeing some of the social and ethical challenges AI might bring, as well as illustrating potential benefits. The description of teachers' attitudes as encompassing a 'swing from total resistance to overreliance' (p. 13) feels particularly prescient, reflecting a current divide between staff in many universities. In a more recent review, Crompton and Burke (2023) consider the disciplinary focus of researchers. They identify discipline-focused reviews in engineering education (Shukla et al. 2019), mathematics education (Hwang and Tu 2021), language learning (Liang et al. 2021), and medical education (Winkler-Schwartz et al. 2019) – but nothing to date in biological education.

In this paper we review research published between 2020 and 2024, analysing the key topics covered and exploring the implications of AI for biological education. We also investigate the use of AI-powered apps of potential interest to biologists (which are poorly covered in many reviews), as well as papers which give a wider picture of how such tools are being used in biological education. We explore knowledge gaps and make recommendations for future research.

Methods

On 14 November 2024, we searched Scopus for all papers containing < chatgpt OR ai OR ‘artificial intelligence’ OR ‘machine learning’ AND education > in the title, abstract or keywords. This yielded 52,387 references, so we refined the search using the inclusion and exclusion criteria shown in Table 1, leaving in 1087 articles that were reviewed manually. Of these, almost half had a focus on computer science (22.2%), medicine (17.2%) and engineering (10.4%), and many mentioned education only tangentially. This left 61 publications for review (Table S2).

We chose Scopus to restrict the search to published articles with an acceptable level of rigour. The cut-off date of 2020 was selected to differentiate our review from two highly cited reviews on AI and education which cover the period up to 2020 (Chen, Chen, and Lin 2020; Zhai et al. 2021), and to encompass the exponential rise in articles on AI and education since 2020. Almost 70% of publications listed on Scopus between 1970 and 2024 containing the terms ‘ChatGPT’ OR ‘ai’ OR ‘artificial intelligence’ OR ‘machine learning’ AND ‘education’ in the title, abstract or keywords were published since 2000, and over 26% in 2024 alone. We narrowed down the search to biological education specifically in line with the focus of this journal.

A recent horizon scan of emerging challenges for teaching ecology highlighted the importance of using new technology, including virtual reality and AI to enhance field-work (Cooke et al. 2020). However, few relevant papers were found in our initial literature review because apps like iNaturalist or Merlin are often mentioned without any reference to the underlying machine learning methods that enable them. These tools employ deep learning algorithms trained on large image or audio data-sets to recognise and classify species, yet their AI components are rarely recognised in the educational literature. We therefore searched the internet and examined the Apple App Store and Google Play to identify 66 AI-powered apps of potential interest to biologists (Table S3). On 20 November 2024, we searched Scopus for all papers containing the name of each app AND ‘education OR student’ in the title, abstract or keywords. This yielded 788 references, covering 28 of the apps. We then filtered the papers following the inclusion and exclusion criteria shown in Table 2, leaving 43 publications for review (Table S4), covering just 14 of the apps (Table 3).

Table 1. Inclusion and exclusion criteria used in the main literature review.

Inclusion	Exclusion
Included in Scopus database	Published before 2020
Original research or review papers	Editorials
Focus on biological education	Medical literature, healthcare, agriculture
Published in English	Not on education or artificial intelligence.

Table 2. Inclusion and exclusion criteria used in the literature review on AI-powered applications.

Inclusion	Exclusion
Included in Scopus database	Published before 2020
Original research or review papers	Not about the app
Focus on biological education	Not on education
Published in English	Medical, healthcare, agricultural literature
Using the AI-powered aspects of the tool	Primarily used for citizen science, not education

Our review focused on the following questions:

- What are the opportunities of using GAI in biological education?
- What are the challenges for using GAI in biological education?
- In what ways are specialised machine learning tools for bioimaging and species identification used in biological education?
- What gaps exist in the literature, and what areas require further research to understand the longer-term impact of AI on biological education?

An inductive coding approach (Fereday and Muir-Cochrane 2006) was taken to identify key themes in the papers selected, answer the research questions posed and identify gaps in the literature. The results of our review are divided into four sections, aligned with the research questions above

Opportunities for using AI in biological education

Enhancing student engagement in biology

Learning and student engagement are most effective when students are supported to achieve just beyond their current level of independent competence. Lev Vygotsky's concept of the *Zone of Proximal Development* (ZPD) delineates this optimal region for learning, where progress occurs through guided support of a teacher or more skilled peer (Vygotsky 1978). In a similar vein, Wood et al. (2021) introduced the idea of *scaffolding* - structured support that helps students solve a problem which would be otherwise beyond their reach. In the case of AI in education, the 'more capable other' of the ZPD may not be a teacher or peer, but a machine acting as a *mediational tool* with AI technologies offering a novel form of digital scaffolding. AI technologies, including computer vision and adaptive learning platforms, can personalise instruction, model expert guidance, and sustain engagement through interactive feedback (Agathokleous et al. 2023; Aleksandrovich et al. 2024; Gibson et al. 2023; Koć-Januchta et al. 2020; Koć-Januchta et al. 2022; Lin 2024; Lytvynova, Nataliia, and Olga 2024; Rahioui 2024; Schmucker et al. 2024).

Adaptive learning, using learning data analysed by AI, allows tailoring of educational inputs or assessments to diverse student groups. For example, Schmucker et al. (2024) trialled a conversational tutoring system to personalise learning in biology classes. Results indicated increased student engagement although not improved learning outcomes. Another study which used advanced algorithms to customise content delivery for individual students reported a 20% increase in student engagement and a 25%

Table 3. A brief description of AI tools cited in published studies included in this review.[1] Tools are ranked by the number of studies that cited them, shown in parentheses. A full list of all 71 AI tools included in the literature search, as well as links to the developers' webpages, is given in table S2.

iNaturalist/Seek by iNaturalist (39) iNaturalist is a citizen science platform for sharing and identifying biodiversity observations, while Seek is a separate mobile app designed for beginners that uses computer vision for instant, real-time identification of plants and animals. The main differences are that Seek requires no account to use, and keeps observations private by default, whereas iNaturalist is for ages 13+ and relies on a community for confirming identifications in its public database.

Google Earth Engine (9) is a Google Cloud product for geospatial analysis at scale. It integrates an extensive geospatial data catalogue with distributed computing, accessible through client libraries. Users can access a wide range of satellite and environmental data, as well as incorporating their own datasets. The platform simplifies geospatial analysis by automatically handling data projection, scaling, and compositing based on user-specified parameters. Its analytical functions operate efficiently across different scales without requiring explicit data preparation. By managing complex data processing and computational scaling internally, Earth Engine enables users to focus on analysis rather than technical setup.

Google Lens (9) is a visual search engine that uses your camera, a photo, or a screenshot to let you "search what you see". It uses AI to identify objects, text, and more, providing relevant information, such as identifying a plant or translating text. It can be used to copy text to a computer, get step-by-step assistance, and explore visually similar images.

ID-Logics (4) is an interactive species identification app that uses a logic-based system to help users identify plants and animals. It operates without an internet connection and provides interactive support, such as short videos for difficult steps, to guide users through the identification process. The app's design prioritizes simplicity and interactivity, offering assistance, traceability, and the ability to save identified species with details like GPS coordinates and photos.

PictureThis (4) is a mobile app that uses AI to identify plants with over 98% accuracy by taking a picture. It provides detailed information on millions of plants, diagnoses plant diseases, offers care tips and reminders, and can identify toxic plants. The app is available on both Android and iOS, with a premium subscription for unlimited features, though a free version is also available.

Pl@ntNet (4) is a citizen science platform and mobile application that uses image recognition technology to identify plant species from photographs. The identification process is powered by a machine-learning algorithm that compares a user's image to a vast botanical database. To ensure accuracy and expand its database, Pl@ntNet leverages a cooperative system that relies on the participation of users with varying levels of botanical expertise.

LeafSnap (3) is a mobile application developed by the Smithsonian Institution, Columbia University, and the University of Maryland that identifies plants, trees, flowers, and mushrooms from user-submitted photos. It uses visual recognition to identify plant species with an accuracy of up to 90%, and its database continually learns and adds new species. Additional features include a plant journal, disease diagnosis, and care reminders.

Merlin Bird ID (3) is a free, AI-powered mobile app from the Cornell Lab of Ornithology that helps users identify birds by photo, sound, or a series of questions about their characteristics. It uses data from eBird, the world's largest bird-sighting database, to provide likely matches with information like photos, songs, range maps, and expert tips.

Plant.id (3) is a mobile tool that uses AI to identify plants and diagnose plant diseases from a photo. Key features include instant plant identification, disease diagnosis and treatment suggestions, a database to learn more about plants, and the ability to manage your plant collection. The app also provides care guides and can identify 90 different diseases, including pests and fungal infections.

Flora Incognita (2) is a free, AI-powered mobile app that helps users identify wild plants by taking photos, and also serves as a citizen science platform for ecological research. Developed by scientists in Germany, the app uses deep learning algorithms to identify thousands of species accurately, even when plants aren't in bloom. Users can document their finds in a personal list and contribute valuable data to studies on biodiversity, climate change, and conservation efforts.

PlantSnap (2) Is a mobile app that uses a photo to identify over 600,000 plants and fungi. It provides additional information such as scientific names, habitats, and care instructions. The app includes a community feature for users to connect and share discoveries and a feature where you can request identification from an expert if the automated system is stumped.

aiplant (1) uses machine learning and a vast plant photograph gallery to identify over 11,000 plant species and provide links to additional information from Wikipedia. It is most effective for plants found in Asia. The app's database grows with user contributions, which are used to train the model.

ForAlexa (1) is an online tool for the rapid development of AI skills for the teaching of evolutionary biology using Amazon's Alexa cloud-based virtual assistant. It allows educators to develop apps quickly and easily for their classes and could be an alternative for students with special needs such as the visually-impaired.

OH!BUG (1) is a digital product developed in the University of Aveiro, Portugal, to connect young learners to plants, by helping them to identify and map the species in their neighbourhood.

improvement in learning outcomes (Aleksandrovich et al. 2024). These authors also report a higher retention rate of students one year later. Other studies are less compelling, however: Similar engagement and learning gains were found when students used an AI-enhanced e-book compared to a standard e-book (Koć-Januchta et al. 2020), and where a natural language processing model was used to enhance learning and assessment in biology through an interactive video game, no assessment was given of its effectiveness (Hernández-Romero et al. 2023). AI has also been used by educators to evaluate engagement in active learning in science classrooms (Adeika, Abiodun, and Owolabi 2024). Although yet to be fully tested, if effective, this would allow educators to undertake real-time assessments of teaching and student engagement.

Enhancing subject-specific knowledge and skills in biology

AI-driven tools can assist in teaching complex biological concepts and support scientific communication, by helping students simplify complex material or tasks (Agathokleous et al. 2023; Braet and Poger 2023; Rahioui 2024; Vaidya and Meenal 2024), acquire practical skills such as species identification (Al-Barazie, Mohamed, and Lin 2024; Hernawati, Muhamad Chaidir, and Meylani 2020; Hubbard 2024), or learn coding for statistical analysis or bioinformatics (Hoffman and Wright 2024; Orench-Rivera et al. 2024). Rapid automated formative feedback has been shown to enhance student understanding of biological concepts, leading to increases in performance of up to 20% (Aleksandrovich et al. 2024; Ariely, Nazaretsky, and Alexandron 2024) plus a 15% boost in knowledge retention (Aleksandrovich et al. 2024). Research using an AI-enhanced e-book in the US (M. M. Koć-Januchta et al. 2022) suggested that the AI-enhanced resource might lead to lower cognitive load and deep learning. However, in the absence of a control group, this study has some limitations.

Quantitative biology has had a tremendous impact on biological research, and Robeva, Jungck, and Gross (2020) emphasise the urgent need for a paradigm shift in undergraduate biology education to integrate data science. There are very few examples of this in the current literature, though the incorporation of AlphaFold2 into an undergraduate module significantly enhanced students' understanding of protein structure prediction and their interest in bioinformatics (Boland and Ayres 2024). An interdisciplinary MSc bioinformatics module using virtual machines to teach core concepts was also popular with students (Johnston, Slater, and Cazier 2022). However, in both studies, lack of control groups and limited evaluation leaves many questions unanswered.

Agathokleous et al. (2023) used ChatGPT to generate 100 important questions facing biological research, noting the opportunities for students to explore these in tertiary biology courses, as well as the potential for GAI to improve students' writing. Critical thinking and writing skills can be enhanced by AI-powered tutoring systems (Ghariz et al. 2024; Steponenaite and Barakat 2023; Yang et al. 2024), while the use of GAI chatbots and virtual tutors are reported to lead to a 35% increase in student satisfaction and a 27% improvement in performance (Aleksandrovich et al. 2024). Al-Barazie, Mohamed, and Lin (2024) used GAI to produce case studies and quizzes helping students identify different pathogenic bacteria. Hubbard (2024) explicitly argues for integrating AI developments into the discipline and puts forward a competency-based model for plant biologists, testing what students can do rather than what they know – in part to avoid some of the escalating assessment issues (see Concerns About Ethics and Academic Integrity).

Supporting inclusivity and student retention

An overview of AI in biology classrooms identifies inclusivity benefits arising from AI use, including assistive technologies such as text-to-speech and predictive text tools which can be used by all students as well as text-to-diagram tools which convert text to Braille for visually impaired students (Yoo 2024). LLMs can also provide translation support for non-native English speakers (Agathokleous et al. 2023) or offer real-world examples which make concepts more accessible across diverse student groups (Boateng et al. 2024; Einarsson, Lund, and Jónsdóttir 2024). In Einarsson's study, abstract concepts from probability theory and statistics were reframed by ChatGPT for targeted groups (including biology undergraduates) and deemed to add value by experts in 72.9% of cases, though student responses were mixed. Rabelo et al. (2022) discuss the potential for Alexa to be used as a resource for students by linking to an online teaching resource. This approach offers considerable advantages for visually impaired students or learners who simply prefer to listen than read.

There are potentially wider system-level advantages of using AI to support inclusion and student retention – though these are not without risks. Machine learning can be used to identify factors influencing academic success in biology, providing data-driven insights into student retention and performance (Bertolini, Finch, and Nehm 2021, 2023; Ding and Ishak 2022; Plumley et al. 2024). Models were trained on student engagement data from the course learning management system, success on previous assessments and a range of other metrics. While this approach can help identify students in need of assistance, it may also lead to labelling impacts or selection of students most likely to succeed at the expense of diversity. Some models incorporate demographic variables such as gender, ethnicity, financial aid and citizenship status, and it is easy to envisage how such datasets could be misused.

Challenges of using AI in biological education

Concerns about ethics and academic integrity

While lecturers recognise the potential benefits of AI in supporting biological education, concerns remain around accuracy, ethics, data privacy, academic dishonesty, and the need for clear pedagogical goals (Fontao 2024; Ghariz et al. 2024; Harper and McCall 2024; Lee and Zhai 2024; Prunkl 2024; Safitra et al. 2024; Steponenaite and Barakat 2023; Titko et al. 2023; Zhang, Fu, and Liu 2022). Concerns have been raised about uncritically adapting pedagogy to incorporate AI (Agathokleous et al. 2023; Dao and Le 2023; Fan, Nazaret, and Azizi 2024; Fontao 2024; Lee and Zhai 2024; Zhang, Fu, and Liu 2022), and over the limited access to tools for some students (Oskotsky et al. 2022). The risk that using GAI tools can lead to replicating existing biases has been raised in the biological education literature as well as elsewhere, as have the risks to teaching quality if GAI tools are over-used, or used to automate tasks such as assessment that arguably should have human input (Agathokleous et al. 2023).

There remains an urgent need to reconsider assessment methods in the face of academic dishonesty, as GAI text becomes more sophisticated and harder to detect (Fontao 2024; Steponenaite and Barakat 2023). Several studies tested the accuracy of chatbots on biological questions and examinations, revealing the strengths and weaknesses of different LLMs (Crowther et al. 2023; Dao and Le 2023; Nguyen and Nguyen 2023). BingChat and Bard excel in factual recall and comprehension, while ChatGPT shows versatility but struggles with complex application tasks. Agathokleous et al. (2023) suggest that tutors concerned about AI-produced assignments should try to generate the same themselves in order to identify work which has been created with GAI, though this would most certainly not be a practical or effective approach! Steponenaite and Barakat (2023) created biology assessment answers in ChatGPT and found that although raw outputs were flagged by plagiarism detectors, use of a paraphrasing tool overcame this in most cases. These authors found that GAI detector tools did identify the answers as partially or fully GAI produced, even after rewriting; however, it's worth noting that larger scale studies (outside biological education) have cast significant doubt on the reliability of such tools (see Weber-Wulff et al. 2023).

Nevertheless, while much of the focus in the literature is on the negative impacts of GAI on assessment, this technology has the potential to enhance education and to promote reliable and authentic assessments (Cotton et al. 2025). Salinas-Navarro et al. (2024) emphasise the need to redesign active learning experiences, focusing on the integration of GAI with authentic assessment and experiential learning. They demonstrate that GAI tools can enhance the formulation, quality and relevance of Intended Learning Outcomes and can support activities across each stage of the experiential learning cycle.

Reduction in critical thinking if students over-use AI tools

Despite the positive findings of some studies on student comprehension and retention of knowledge, there have also been concerns about a decline in critical thinking and independent research skills if students become over-reliant on GAI (Agathokleous et al. 2023; Fontao 2024; Lee and Zhai 2024). Fontao (2024) asked student teachers (including biologists) about potential advantages and disadvantages of AI for teaching, and a reduction in information searching and critical analysis skills amongst pupils was a major concern – though humanities students were more concerned by this than science students. Lee and Zhai (2024) also worked with student teachers in science disciplines who suggested using a range of sources specifically to counter potential disinformation coming from GAI tools. They recommend implementing structured classroom interactions (such as group discussions or student-led presentations) to reduce dependence upon GAI amongst pupils and note that a programme of digital literacy development for both students and teachers might be needed to make best use of the technology.

Need for professional development around AI for biology teachers

While many students exhibit high acceptance of AI-powered software (Henrich et al. 2023) this is not echoed amongst educators (Nazaretsky, Cukurova, and Alexandron 2022). Professional development for biology educators should prepare them to integrate AI into their teaching by increasing their confidence and competence (Adelana, Ayanwale, and Sanusi 2024; Cooke et al. 2020; Fong et al. 2022; Fontao 2024; Henze et al. 2022; Lee and Perret 2022; Lee and Zhai 2024; Titko et al. 2023; Tretter et al. 2023).

Examples of potential uses of AI which may be less familiar to teachers include neural network models which can predict the difficulty of teaching material, allowing for refinement by the lecturer (Phillips, Saleh, and Ozogul 2022). Given the speed of GAI developments, guidance on its use to generate (Al-Barazie, Mohamed, and Lin 2024), rephrase (Einarsson, Lund, and Jónsdóttir 2024), or fine-tune assessments (Crowther et al. 2023) would also be beneficial. Machine learning also has the potential to mark and provide feedback on students' work, at least in low-stakes assessments. In higher education, a Natural Language Processing model achieved a high-level of agreement with human experts at marking biology questions (Ariely, Nazaretsky, and Alexandron 2023), and a predictive text analysis model trained on students' biology essays, showed very good agreement with lecturers' grades (Sripathi et al. 2023). Based on this, the authors released the Constructed Response Classifier tool as a free web-based resource to evaluate students' responses to questions. At a wider level, Gibson et al. (2023) discuss the need for rethinking learning theory in the age of AI, arguing that increasing use of GAI in teaching, learning and assessment calls for a reconsideration of what it means to learn something. These authors draw on computational biology, complexity science and developmental psychology to model the roles of AI in promoting learning processes.

Detailed recommendations for biology teachers on professional development are beyond the scope of this review, but there are many useful resources. Within the UK, the underlying policy and guidance documents on GEN AI in education are provided by the Department for Education (2025), who also provide support materials. Further information and guidance on professional development can be found in recent publications from EDUCAUSE (Robert and Muscanell 2023) and JISC (Webb 2024).

Use of specialised machine learning tools in biological education

Enhancing student engagement in biology

As with the use of AI generally, one major advantage of using AI-enhanced tools in biological education is their potential to enhance student engagement and foster a stronger connection with nature (e.g. Ayers 2024; Baumann, Groß, and Michelsen 2023; Echeverria et al. 2021; Martins and Santos 2023). Platforms like iNaturalist encourage hands-on learning and a sense of environmental stewardship, making biology more interactive and accessible. Whilst iNaturalist was by far the most popular tool in biological education (Table 3), other tools produced similar results. ID-Logics was found to enhance engagement with species identification and biodiversity (Baumann, Groß, and Michelsen 2023), and students reported a higher level of enjoyment using this AI-tool than a similar paper-based ID tool (Finger, Groß, and Zabel 2022). Subsequent research (Finger, Groß, and Zabel 2022) found similar increased enjoyment and motivation, but more so for male students than females, offering an interesting hint at potential gender differences which remain largely unexplored in the literature. Bio Sketchbook, an AI-assisted sketching tool, has also been explored in a preliminary study involving only 6 children, which showed that the tool helped motivate children to observe and learn about different plants (Zhang et al. 2021).

iNaturalist is also promoted as a tool for enhancing student collaboration, motivation and engagement (e.g. Echeverria et al. 2021; Ickert-Bond and Kaden 2022). Unger used it to engage undergraduates in aquatic ecology (Unger et al. 2021) and to teach about ethograms in animal behaviour (Unger 2023), in both cases stimulating student interest and enhancing engagement. In another study, 80% of teachers agreed that students collaborated more when the apps were implemented into classes and over 71% agreed that there had been positive effects on students' interest in lectures and in science (Schmidthaler et al. 2023). However, very few studies involve comparator groups, and when they do the results are somewhat less dramatic. For example, curiosity about the identification of insects increased by 39% and interest in entomology by 16% among biology students following an activity using iNaturalist, with far lower values (18% and 0%) recorded for students on more applied courses such as forestry and environmental science (Mech et al. 2022). Smith et al. (2021) report that exercises using Seek and iNaturalist increased students' interest in nature and science, self-efficacy for environmental action, and for learning and doing science but overall, the only significant increase was interest in science. Similarly, Tillotson-Chavez and Weber (2024) found no significant increase in the likelihood of biology students continuing to use iNaturalist, although they would recommend it to others and agreed that accurate species identification was important. A systematic review of iNaturalist use in biology education emphasises its potential in allowing students to contribute to a community of researchers (Rode and Torkar 2023). Whilst most authors only considered local collaboration between students, opportunities for international collaboration were noted in two cases (Hitchcock, Sullivan, and O'Donnell 2021; Ickert-Bond and Kaden 2022).

Enhanced nature connection or environmental stewardship was another oft-cited benefit, for example, through overcoming biodiversity naivety or 'plant blindness' (e.g. Finger, Groß, and Zabel 2022; Niemiller, Mark, and Matthew 2021; Rode and Torkar 2023; Tiago, Evaristo, and Pinto 2024). It is increasingly common for iNaturalist to be used in student citizen science projects (e.g. Forti 2023), or to support a 'BioBlitz' on university campus (e.g. Gass et al. 2021; Rokop et al. 2022). Where iNaturalist was used to support project-based learning in HE, 70% of students involved stated that the project increased their sense of nature connectedness and over 90% said that they would continue to use it (Forti 2023). Similarly, 82% of students involved in a campus bioblitz considered it a valuable hands-on learning experience, and most noted that their sense of environmental stewardship had increased (Gass et al. 2021). Qualitative comments suggest that learning outside the classroom, authentic learning, and an opportunity to see their local environment differently were key benefits. Over 60% of students in Rokop et al. (2022) found the activity very or extremely engaging, but just 30% said they were very or extremely likely to engage in citizen science in the future and only 34% felt strongly that the activity had provided important information. This variation might be explained by the level of experience of participants and their inherent biological interest. In another study, biology and geography researchers and students collected significantly more BioBlitz observations than did other cohorts (Tiago, Evaristo, and Pinto 2024). Nonetheless, there is evidence that the use of AI-powered apps can stimulate an interest in the natural world. Using Google Lens and Seek by iNaturalist to learn about nature had a stronger effect on nature connection than simply spending time in nature, at least amongst those participants with higher levels of engagement in the activity (Ng, Leung, and Chan 2023). Similarly, Potsikas et al. (2023) found that participation in a BioBlitz using iNaturalist produced a statistically significant increase in students' connectedness to nature scores (Mayer and Frantz 2004).

Enhancing subject-specific knowledge and skills in biology

The integration of AI tools in biological education may enhance scientific skills such as observation, data collection, and ecological analysis – although research evidence in this area is rather weak. Perceived improvements in understanding as a result of using iNaturalist have been reported, with one study showing that 53% of undergraduates felt it greatly increased their comprehension of ecological concepts, and 93% their numerical understanding of biodiversity (Forti 2023). Two other studies found self-reported increases in biodiversity knowledge among students following activities using iNaturalist (Gass et al. 2021); however, in neither of these studies was there a direct assessment of learning. Eden (2023) used iNaturalist as a tool for inquiry-based learning at school, encouraging students to identify local organisms and create a presentation to share their findings. The author suggests that this approach allows students to take ownership of a project and control their own learning – though no formal evaluation is cited. Other papers include evaluation but rarely have a comparator group. For example, using iNaturalist for an exercise on pollinator interactions (Tillotson-Chavez and Weber 2024) and on the rocky shore (Neves, Boaventura, and Galvão 2024) significantly increased results in post- versus pre-activity tests, but the lack of any point of comparison limits attempts to judge the effectiveness of the method itself. Similarly, a small study found that children were able to answer plant identification questions well after using BioSketchbook, but the lack of a control limits our interpretation of this result (Zhang and Begum Aslan 2021).

Studies including more rigorous evaluation have found mixed results – students using the ID-Logics tool demonstrated increased competence at identification and enhanced data processing skills (Baumann, Groß, and Michelsen 2023). The tool allowed students to develop an identification key for any group of living organisms and led to improved communication, collaboration, information search and evaluation skills. The ID-Logics tool was also evaluated on a school field trip in Germany where researchers found that, although students enjoyed engaging with it, identification success was actually lower (and slower) than with a paper-based tool (Finger, Bergmann-Gering, and Groß 2022). However, the paper-based tool was specifically designed for this geographical environment and thus had fewer options available; while useful scaffolding for learners, this may mean that the students' learning is less transferable to other environments where the species distribution at the site is unknown. Linked to this is the finding that though motivation was increased using the ID-Logics tool, perceived competence was actually rated as lower when using the app (Finger, Groß, and Zabel 2022). Various studies using the PlantNet app (Coşkunserçe 2024; Iskrenovic-Momcilovic 2023) have shown increases in scores on tests conducted before and after an activity. Iskrenovic-Momcilovic (2023) demonstrated that a field-based approach using the PlantNet mobile app contributed to the higher test scores and better long-term retention of knowledge when compared to a classroom-based exercise with a digital herbarium and printed handbook. In another comparative test, two versions of an app designed for school children were used, a narrative-only variant and another including narrative, computer vision, and augmented reality (Cheng et al. 2023). Both were found to be engaging and increased learning significantly using pre- and post-intervention tests, but interestingly the narrative-only app performed as well or better. We suggest, therefore, that increases in learning and engagement in some studies may be due to an effect of novelty or time on task, rather than to the use of an AI-powered app specifically.

Supporting inclusivity and student retention

Apps such as iNaturalist have proven useful in supporting asynchronous delivery of teaching for hard-to-reach rural students (Ickert-Bond and Kaden 2022), and for distance learning more widely during the COVID-19 pandemic (Gerhart et al. 2021; Peregrym et al. 2022). Ayers (2024) reports the use of Universal Design for Learning principles to offer an inclusive interactive approach for Deaf and Hard of Hearing and English Language Learner students through integrating Seek by iNaturalist into science education, facilitating multi-modal nature-based sensory experiences. They argue that Seek enables student-centred learning in diverse classrooms and that it enhances inclusive and accessible learning, fostering engagement with the environment and promoting science literacy. It has also been suggested that iNaturalist can improve mental health among university students by facilitating access to campus green spaces and activities in natural environments (Waite 2024). Most studies used commercially available tools, but Rabelo et al. (2022) developed *ForAlexa*, which fine-tunes the interactions between the user and Amazon Alexa. They developed sets of evolutionary biology questions that Alexa could respond to verbally, but *ForAlexa* allows educators with some programming skill to develop apps for different subject areas. *ForAlexa* could also be used to support visually impaired students by providing an alternative to written material.

Challenges of using specialised machine learning tools in biological education

Fewer challenges arose from using these tools in biological education than from GAI. Mobile apps like iNaturalist were rapidly mastered by most students, producing high-quality data (Niemiller, Mark, and Matthew 2021; Stevenson, Merrill, and Burn 2021), and while some authors raised issues around accuracy and data quality (Bilyk et al. 2020; Hart et al. 2023; Mäder et al. 2021; Niemiller, Mark, and Matthew 2021; Schmidt et al. 2022; Soroye et al. 2022), most studies mentioned few, if any concerns, over ethics and academic integrity. Baumann, Groß, and Michelsen (2023) identify technical issues as a concern for students developing an identification key, but this came up rarely in other papers where proprietary tools, often intended for citizen science projects, were considered easy to use and not requiring high-level technical skills.

Where issues arose, these were generally mild – inadequate photos taken for upload on iNaturalist (Potsikas et al. 2023) or difficulties encountered by very young children who struggled to hold the iPad (Zhang et al. 2021). Occasionally, students needed additional assistance using the more demanding ‘ID-Logics’, which mimics a taxonomic key (Groß et al. 2020). Other concerns raised included inaccuracy of student submissions and copyright infringement if students uploaded photos to iNaturalist which were not their own (Niemiller, Mark, and Matthew

2021). The authors suggest that instructors remain vigilant and use examples of poor practice as 'teachable moments'. However, overall, they describe extensive use of iNaturalist with students and encountered few problems. In a survey of school teachers, most respondents were generally positive about the use of AI tools, though some raised concerns about a lack of devices, poor internet connectivity, uncertainty over links with the curriculum or the scientific accuracy of information (Schmidthaler et al. 2023). Concerns have been raised that apps like Seek do not encourage the students to engage with the organisms except via the lens of their phone. This limited sensory modality may mean that they fail to appreciate smell or touch and perhaps the wider environment organisms inhabit (Cederqvist and Thorén Williams 2023).

As noted earlier, one challenge identified by Rode and Torkar (2023) and Waisome et al. (2023) is insufficient preparation of teachers. However, others suggest that there is no need for professional development as these tools are generally intended to be used with minimal instruction. Indeed, some studies reported that teachers found the AI-powered tools engaging (Canuto 2023; Waisome et al. 2023) and that they helped improve their own understanding (Cederqvist and Thorén Williams 2023). Waisome et al. (2023) even went as far as using Shark AI to train student teachers about the fundamentals of AI and the importance of curriculum design for technology implementation, rather than about biology *per se*.

Gaps in the literature around AI in biological education

One of the limitations of the biological education literature is the dearth of large-scale studies. Much of the literature outlined above is based on individual case studies with varied levels and quality of evaluation. National or international surveys collating examples of AI use in biological education would offer a wider view of the field, or indeed a Delphi study using experts in biological education to identify key issues. As in much of the education literature – and made particularly severe owing to the recency of technological developments – longitudinal studies in biological education are lacking. While some research demonstrates the effectiveness of AI tools in enhancing engagement and performance, there is limited research on the long-term impact of AI-driven approaches on student retention, comprehension, and career outcomes in biology. More longitudinal studies are needed to assess sustained learning benefits and potential drawbacks over time (see Holmes, Bialik, and Fadel 2019). Concerns about the influence of GAI on critical thinking, creativity, and potential overreliance by students also need further investigation, including research which explores strategies to integrate AI in ways that foster skills rather than replace them. Studies have investigated student engagement but rarely address student perceptions of AI tools in biological education, including factors influencing their readiness to use AI (Zawacki-Richter et al. 2019). Research on how students view the role of AI in their education and career preparation could inform the design and delivery of AI-enhanced biology programmes.

Most papers focused on the implementation of AI tools in classroom or lab-based settings. More research is needed to explore the potential of AI in fieldwork, such as environmental monitoring, biodiversity studies, and ecological modelling. There is also relatively little research which explores assessment issues beyond the academic integrity realm. Authentic assessment using GAI tools is rarely mentioned by authors in this review, despite considerable interest in the wider education literature. Although many of the papers touched on ethical concerns relating to academic dishonesty and data privacy, there was little in the way of detailed evidence or advice. There is a need for comprehensive, field-specific ethical frameworks and guidelines for integrating AI in biology education. These should address unique issues in biology, such as the handling of sensitive data in bioinformatics or the ethical use of AI in ecological and environmental education (Holmes and Porayska-Pomsta 2022; Holmes et al. 2021). In a similar vein, although addressed in some papers (Niemiller, Mark, and Matthew 2021; Stevenson, Merrill, and Burn 2021), disparities in access to AI tools and resources may impact students from particular socio-economic backgrounds (Schmidthaler et al. 2023). Further research is needed to ensure equitable access to AI-driven educational opportunities across all student demographics.

The integration of AI into biological education is not without a degree of irony. One example is the use of AI-driven platforms such as iNaturalist and Merlin, which employ complex computational processes to foster nature connection. These systems can enhance learning and engagement, yet they do so through layers of technological mediation that may distance the learner from direct sensory engagement with nature. Moreover, Biology as a discipline emphasises sustainability, ecological balance, and a deep understanding of environmental impacts, including climate change. But both the training (Strubell, Ganesh, and McCallum 2020) and driving (Luccioni, Jernite, and Strubell 2024) of artificial intelligence models demand a huge amount of energy, much of which comes from non-renewable sources. There are significant questions about whether these core values are in conflict with the use of AI systems that contribute to carbon emissions (Wang, Li, and Li 2024), yet this was an area that was almost completely absent in the literature reviewed here. There is potential for future research to explore the ways in which biology teachers and lecturers balance these ethical and conceptual contradictions and grapple with the tensions between potential benefits for students through using AI tools versus environmental damage cause by their use. Further research could usefully be undertaken which attempts to quantify the carbon footprint of AI in biological education, identify possible mitigations and assess the availability of alternative tools with lower carbon footprint.

Conclusion and recommendations

This review illustrates the breadth of activities in biological education which are being supported by AI and identifies some of the key benefits and challenges with its use. Benefits include enhanced student engagement, accessibility and personalised learning; challenges include academic integrity, ethical and copyright issues, and sustainability concerns. There is comparatively little literature which is specific to biological education, and many of the issues which arise in this review echo those identified in other disciplines (Eysenbach 2023; Sallam 2023). Unlike many previous reviews, we look beyond the use of large language models to consider uses of AI in biological education contexts such as fieldwork. AI tools like iNaturalist, adaptive learning systems, and generative AI have demonstrated the potential to make biology education more interactive and accessible.

These tools can support diverse learning needs, improve scientific literacy, and foster environmental stewardship.

However, evaluation of GAI and AI tools in biological education contexts is relatively under-developed – with many papers reviewed here discussing the use of such technologies, but with little formal evaluation as to their effectiveness. This greatly hinders the interpretation of research, as many studies lack explicit questions, fail to identify the core competencies they wish to assess or enhance, and rely on anecdotal or perception-based results. In the context of biology education research on AI, a design-based research approach as advocated by Scott, Wenderoth, and Doherty (2020) may be helpful. Design-based research is grounded in theories of learning but was developed from methodologies employed by engineers to test products designed for specific purposes. It has been used successfully in a study on the technological resources used in a blended learning environment in ornithology (Vera-Morales, Jaime, and Andrea 2021), but not yet to study AI within biological education.

In addition to the educational benefits identified in this review (increased engagement, learning and inclusivity), there is mounting evidence that AI will impact the working lives of young people in significant ways, and educators need to help students prepare for their future professional lives. As GAI becomes more ubiquitous, increasingly embedded into search engines and word processing software, the balance of arguments in the debate about its use in educational contexts is shifting. Students need to know how to use AI for positive purposes such as enhancing species identification, reviewing large data sets, image analysis and statistical support, and educators should assume that GAI will be used in assessments unless conducted face to face. However, many biology educators lack the training needed to incorporate AI tools effectively into their teaching, and UK institutions have not radically changed their approach to assessments (Freeman 2024). This highlights the need for professional development and much clearer guidance and governance around AI and academic integrity. Freeman (2024) found that only 22% of undergraduates were satisfied with the support they had received on AI and that universities needed to develop clear policies on acceptable and unacceptable uses of AI. This requires national leadership, building on the work started by the Russell Group (2024), the Royal Society (2023) and the Quality Assurance Agency for Higher Education (2023a; 2023b).

It is becoming increasingly clear that the Biology curriculum needs updating to include AI competencies and to equip students with relevant skills that meet the challenges of modern biological research and graduate employment contexts (Chen et al. 2024; Cooke et al. 2020; Hubbard 2024; Kumar 2021; Kumar et al. 2023; Patel, Pillai, and Toby 2023; Safitra et al. 2024; Sandfort et al. 2024; Shin et al. 2024). Students must understand how to check the authenticity and accuracy of GAI output (including checking for biases in the output), and they need to take responsibility for ethical use of AI. GAI is a technological leap, and it is forcing us to reflect on how we teach and assess (Cotton et al. 2025). As well as integrating AI into teaching, assessment methods must be revised to ensure academic integrity and evaluate higher-order skills, such as critical thinking and creativity. The widespread use of GAI raises issues of navigating misinformation, academic dishonesty and data privacy. Students and teachers alike must develop digital literacy to mitigate these risks.

And educators should be asking themselves: What does it mean to be a biologist in the age of AI?

Note

1. Note that these descriptions come from the developers and the claims made about the comprehensiveness or accuracy of their products have not been verified.

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