

SUSTAINABLE DEVELOPMENT AND ARTIFICIAL INTELLIGENCE: CONVERGENCES, TENSIONS, AND GEOGRAPHICAL, SPATIAL, AND TERRITORIAL CHALLENGES FOR CONTEMPORARY EDUCATION

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Abstract: Amid accelerating ecological, social, and technological transformations, education is confronted with the dual challenge of addressing sustainability imperatives while adapting to the disruptive rise of artificial intelligence (AI). This article investigates the intersections, frictions, and pedagogical implications that emerge when sustainable development, geography, and AI are integrated within contemporary learning environments. Using the AinDraham forest in Tunisia as a case study, the research demonstrates how spatial and territorial approaches, combined with machine learning techniques and augmented reality applications, can open new pathways for innovative and transformative educational practices. The study proposes a framework in which AI is not only positioned as a technical tool for ecological modeling and scenario planning but also as a medium for fostering critical inquiry, ethical reflection, and civic participation. Through the integration of data-driven analysis, geospatial modeling, and immersive technologies, learners are encouraged to move beyond abstract theorization and to actively engage with the complexities of real-world sustainability challenges, cultivating a form of applied ecological citizenship. Nevertheless, the findings also bring to light a number of structural and ethical constraints, including concerns related to data reliability, persistent digital divides, and the pressing need for teacher training that encompasses both technical competence and reflective capacities. Ultimately, the research advocates for a context-sensitive and progressive integration of AI and geography within sustainability education, positioning schools and universities as experimental spaces where innovation, territorial awareness, and collective responsibility can be reimagined.

Keywords: sustainable development, geography, geospatial, territoriality, artificial intelligence

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INTRODUCTION

In the face of accelerating ecological, social, and economic crises, sustainable development has ceased to be an optional ideal and has instead become a global imperative. At the same time, artificial intelligence (AI) is profoundly reshaping societies by reconfiguring modes of production, communication, and learning. These two dynamics, sustainability and AI, emerge as among the defining forces of the twenty-first century. Their intersection within education raises crucial questions about the purposes of schooling, the formation of citizens, and the role of educational institutions (Tilbury, 2011).

Sustainable development is no longer merely a hopeful vision of the future. With climate crises intensifying, social inequalities widening, and natural resources being depleted, it has become a pressing necessity. The United Nations' 2030 Agenda and its 17 Sustainable Development Goals (SDGs) place education at the heart of this transition. In particular, SDG 4 "Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all" emphasises the role of schools in building societies that are just, inclusive, and ecologically responsible (UNESCO, 2021). In this light, immersive technologies such as augmented reality (AR) emerge as promising pedagogical tools. By engaging students in interactive, context-rich experiences, AR can help make the abstract tangible, revealing the impacts of human choices on the environment and fostering more active and engaged learning about ecological and social transitions.

Simultaneously, AI asserts itself as one of the major innovations of our era. When coupled with the aims of sustainable development, it becomes a structuring force of the twenty-first century. Their articulation in educational settings opens up a critical space for reflecting on the ultimate goals of schooling, the ways in which citizens are educated, and the responsibilities of educational institutions. AR-based tools allow learners to interact with dynamic simulations for example, visualising how an ecosystem evolves under different climate scenarios, or showing how everyday practices (energy use, waste management, mobility) affect carbon footprints. Such experiences give students a more concrete and transformative understanding of ecological and social transitions, contributing to sustainability-oriented education.

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Sustainable Development: An Educational Framework for the 21st Century

Since the Brundtland Report by the World Commission on Environment and Development (1987), sustainable development has been understood as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” In the context of global urgency including climate change, resource depletion, and growing social disparities this concept has shifted from theory to essential practice. The UN’s 2030 Agenda and its 17 Sustainable Development Goals (SDGs) reaffirm the central role of education in ecological and social transition (UNESCO, 2021). SDG 4, in particular, aims to “ensure inclusive and equitable quality education and promote lifelong learning opportunities for all.” It foregrounds critical thinking, solidarity, global citizenship, and ecological awareness competencies essential to navigating today’s challenges and forging resilient, just societies (UNESCO, 2017). Teacher-training institutions bear a special responsibility: to embed Education for Sustainable Development (ESD) within curricula, foster systems thinking (Sterling, 2001), and ensure institutional governance aligns with sustainability principles (Tilbury, 2011). Sustainable education must go beyond theory, requiring participatory pedagogies, interdisciplinary approaches, and hands-on experiences that nurture citizen engagement.

In Tunisia, preparing teachers is a strategic lever for cultivating responsible, critical citizens. Educator training institutes find themselves at the nexus of multiple transitions. They need to equip future professionals to harmonize sustainability and digital culture by integrating:

- ESD and systems thinking in curricula (Sterling, 2001);
- Modules on digital literacy and AI ethics;
- International exchange projects to strengthen global citizenship (Tarozzi & Torres, 2016);
- Participative and sustainable educational governance.

Artificial Intelligence: Pedagogical Opportunity and Ethical Challenge

Artificial Intelligence (AI) refers to technologies capable of replicating certain human cognitive functions such as reasoning, learning, or perception. In education, its applications are diversifying and becoming more established: personalized learning pathways, predictive performance analytics, early detection of learners’ difficulties, automated feedback generation, and adaptive learning environments (Luckin et al., 2016). These innovations offer the promise of more responsive, individualised, and inclusive education, better suited to increasingly diverse student populations. The European Commission, for instance, identifies education as a strategic domain for AI deployment, especially through its Digital Education Action Plan 2021-2027 (European Commission, 2021). This plan advocates for deeper integration of digital technologies in European educational systems, positioning AI as a lever of pedagogical and organizational transformation.

However, widespread adoption of these technologies raises ethical and socio-political challenges. The massive collection of learning data raises concerns about privacy and data security. Predictive algorithms risk turning education into a system of surveillance, where every performance is tracked and normalized. Moreover, algorithmic bias inherent in many AI models can reproduce or amplify existing inequalities, compromising educational equity (Floridi & Cowls, 2019). The digital divide further threatens to exclude some learners and educational institutions from the benefits of innovation.

Given these stakes, it is crucial to avoid reducing education to mere algorithmic performance. Teacher training in digital literacy and AI ethics becomes a *sine qua non* for fostering critical and citizen-oriented appropriation of AI. More than that, schools must remain reflective spaces where the purposes of digital tools are interrogated: their goals, their uses, and their impacts on core values like autonomy, freedom, and equality among learners.

The pedagogical issue is not only technical but deeply political and democratic. AI’s relationship with sustainability is profoundly ambivalent. On one hand, AI offers major leverage for achieving the SDGs: applications range across biodiversity monitoring via automated satellite image analysis, modeling and forecasting natural disasters to anticipate climate risk, energy optimization in buildings and smart grids, and remote medical diagnostics improving healthcare access in remote regions (Rolnick et al., 2019; Rolnick et al., 2022). Within education, AI can enhance inclusion through tailored learning experiences and contextualized ecological and sustainability content, thereby deepening learners’ understanding of environmental and social challenges. AI also opens unprecedented opportunities for active, experiential learning. Interactive simulations, predictive analytics, and immersive scenarios allow students to visualize complex interdependencies between human societies and eco-systems making visible what often remains abstract.

Such devices, combining scientific data with pedagogical mediation, help cultivate what might be called an “augmented ecological consciousness” among learners (Fridhi et al., 2020).

Yet, integrating AI in education for sustainability must not be merely instrumental. It demands forming reflective citizens, able to analyse both benefits and limitations of these technologies. Pedagogical aims should go beyond technical knowledge toward critical capacities: questioning innovation goals, anticipating social and environmental impacts, and envisioning more responsible technological alternatives. In this sense, AI becomes not only a teaching tool but also an object of study, inviting students to reflect on how innovation and sustainability may be reconciled (Fridhi et al., 2018).

Modelling Capabilities and Educational Value

One of the key contributions of artificial intelligence (AI) to sustainable development lies in its ability to model complex systems and project multi-factorial scenarios. Machine learning techniques such as random forests and gradient boosting and deep neural networks (e.g. CNNs, spatio-temporal LSTMs or Transformers) now enable prediction of environmental events (droughts, heat waves), detection of anomalies (deforestation, land cover change, pollution), and simulation of biodiversity dynamics or policy impacts (Bekkar et al., 2020).

From an educational perspective, such models become powerful levers for experiential learning: learners can work with real datasets, test “what-if” hypotheses (e.g. “what happens if mean temperature rises by +2 °C?”), compare alternative scenarios, and develop genuine socio-ecological data literacy. This literacy includes not merely reading and interpreting indicators, but critically understanding uncertainties, error margins, and inherent biases in models. These pedagogical tools may take the form of interactive scenario simulators (e.g. “what if ...?” platforms) that invite learners to assess consequences of collective or individual choices on territorial evolution. Augmented reality (AR) or virtual reality (VR) further enrich this experience by rendering local impacts tangible for example, soil salinization or water stress in a given region. Moreover, contextualised data narratives such as story maps bridge scientific outputs with territorial narratives, making ecological phenomena more accessible and meaningful. By mobilising such approaches, education ceases to be a top-down transmission of knowledge: it becomes a space for co-construction, where learners acquire analytical, technical, and civic competences while deepening their ecological engagement. In countries highly exposed to climate change, like Tunisia (Ministry of Local Affairs and Environment, 2021), AI can support the construction of territorially grounded ecological profiles at the governorate, delegation, or watershed scale.

For modeling-derived ecological profiles to function as genuine learning artefacts, one must design an integrated pedagogical approach structured around three complementary dimensions.

Integrated Pedagogical Design

The proposed pedagogical framework is holistic, combining learning objectives, instructional situations, and assessment modalities. It targets (1) conceptual appropriation of socio-ecological notions of risk, vulnerability, and resilience (Folke et al., 2010); (2) methodological skills in data modelling and interpretation (Luckin et al., 2016); and (3) environmental citizenship through ethical judgment and informed decision-making (UNESCO, 2017).

To realize these aims, several instructional settings are deployed:

- Participatory modelling workshops, where learners co-design local indicators (e.g. water, soil, heat stress) from open data or field measurements (Reed et al., 2013).
- Territorial case studies, focused on specific local contexts (e.g. Cap Bon, Nefzaoua), guiding learners to elaborate adaptation scenarios (e.g. water-efficient irrigation, targeted reforestation).
- Augmented reality overlays, enabling layers such as historical NDVI indices or water stress to be superimposed on local maps, thereby visualising ecological trajectories (Ibáñez & Delgado-Kloos, 2018).
- Ethical scenario debates, which challenge students to arbitrate trade-offs among cost, equity, and effectiveness using divergent risk profiles (Biesta, 2010).

Assessment covers multiple dimensions: technical (mini-modeling projects with cross-validation and performance metrics, à la Goodfellow et al., 2016), critical (analysis of model interpretability and bias, following Floridi & Cowls, 2019), and civic (design and monitoring of “low-carbon” action plans with school-level carbon or water consumption indicators, as inspired by Sterling, 2010).

Voici une traduction académique et humanisée en anglais, respectant le style de votre article :

Pedagogical Case Study: Ecological Modeling of the AïnDraham Forest through AI

The AïnDraham forest, located in the Kroumirie region in northwestern Tunisia, represents an exceptional ecological heritage. It hosts a dense concentration of cork oak trees (Figure 1 and Figure 2), along with several endemic plant species and a remarkable diversity of wildlife.

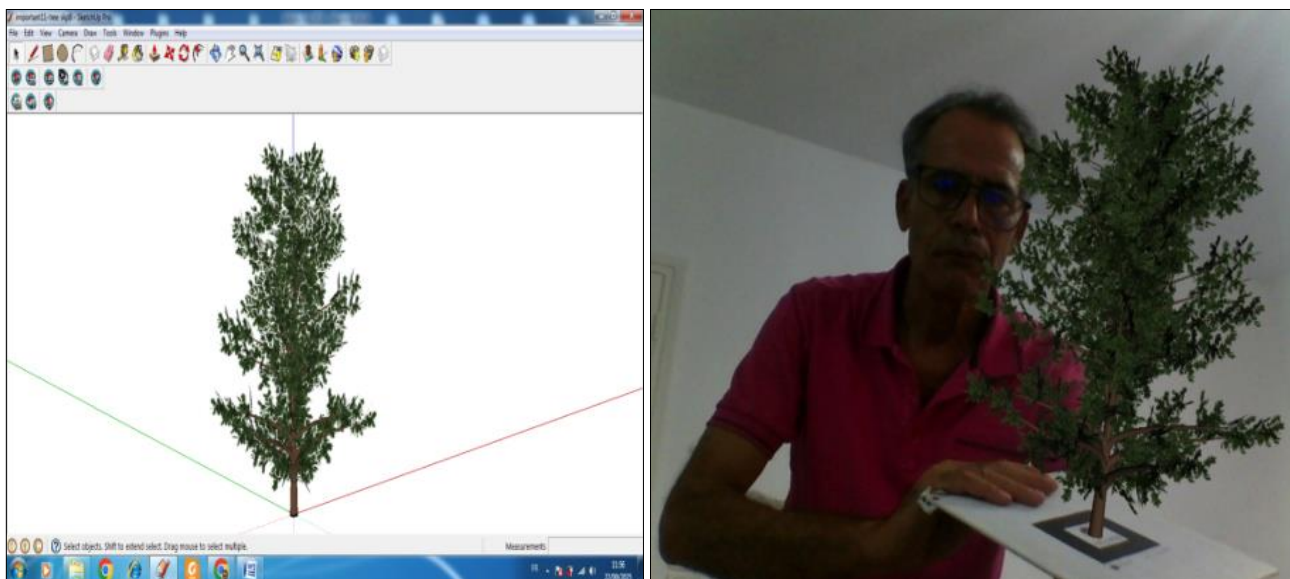


Figure 1. Oak tree 3D modelling of an oak tree Application of Augmented Reality on the 3D model of an oak tree

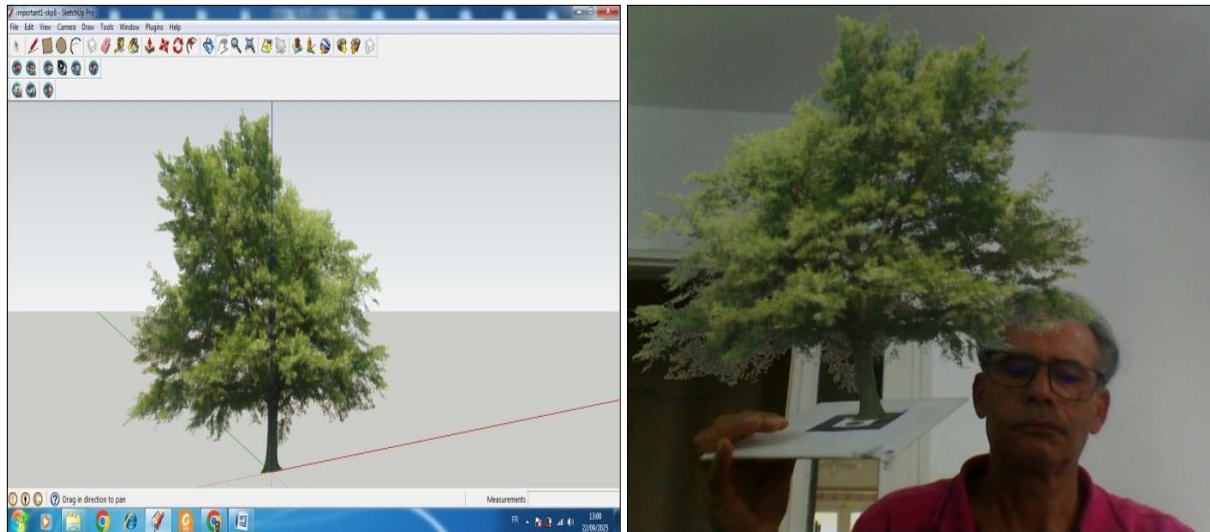


Figure 2. Cork tree 3D modelling of a cork tree Application of Augmented Reality on the 3D model of a cork tree

However, this area is currently under multiple pressures, including recurrent wildfires, illegal deforestation, unplanned urban expansion, and the cumulative effects of climate change. From a pedagogical perspective, these challenges can serve as the foundation for an AI-assisted ecological modelling project, enabling students to engage in a full cycle of scientific investigation and to generate actionable insights for environmental management.

MATERIALS AND METHODS

Data Collection and Assembly

- Satellite imagery: Utilisation of Sentinel-2 and Landsat datasets to analyse forest cover and its temporal dynamics.
- Climatic data: Integration of global databases, such as WorldClim, to monitor temperature and precipitation trends over time.
- Field observations: Educational field trips during which students conduct floristic and faunistic inventories, record signs of environmental degradation (e.g., wildfires, soil erosion), and supplement existing datasets.

Processing and Learning

- Model construction: Development of machine learning models, including Random Forests and neural networks, to establish correlations between climatic variables, forest cover, and local biodiversity (Figure 3, 4, 5, and 6).

This pedagogical sequence enables students to actively engage with real-world ecological data, fostering analytical skills, scientific reasoning, and an applied understanding of environmental dynamics, while providing insights that can inform sustainable management practices.



Figure 3. 3D modeling, State of the cork oak forest before the year 2025



Figure 4. Application of Augmented Reality (AR) on the 3D model: State of the cork oak forest before the year 2025



Figure 5. 3D modeling, state of the cork oak forest in 2025



Figure 6. Application of Augmented Reality (AR) on the 3D model: State of the cork oak forest Year 2025

Prospective Scenario Simulation

- Scenario A: +2 °C in average temperature → retreat of wetlands, upward migration of plant species, and increased wildfire risk.

- Scenario B: -10 % forest cover → habitat fragmentation, loss of ecological connectivity, biodiversity decline, and exacerbated erosion and water stress.

Students compare the ecological and social impacts of these scenarios and critically discuss their plausibility.

RESULTS VISUALIZATION AND COMMUNICATION

- Production of interactive, dynamic maps using QGIS and Google Earth Engine.
 - Creation of story maps to contextualize results (before/after, Scenario A/B).
 - Oral presentation of conclusions to a wider audience (teachers, local stakeholders, other students), simulating a territorial management committee.

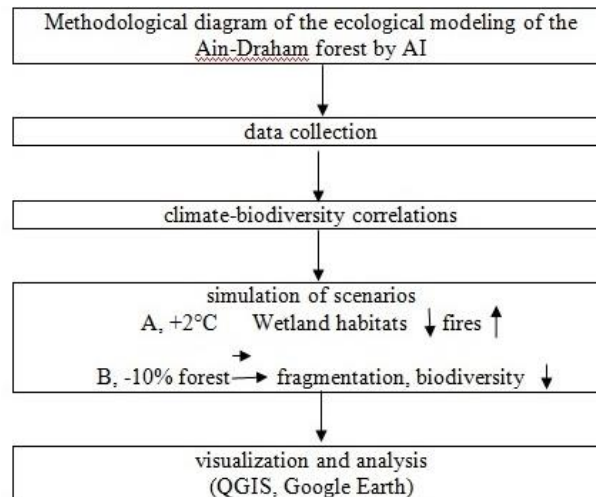


Figure 7. The methodological diagram of the ecological modeling of the AinDraham forest by AI

An Innovative Pedagogical Approach Integrating Artificial Intelligence

This educational experience demonstrates how artificial intelligence (AI) can be effectively integrated into an educational sequence. It positions learners as researchers, engaging them in an active investigative process and enabling them to produce tangible and transferable results. Far from being a mere technological abstraction, AI here serves as a tool for environmental education and sustainable development.

It offers dual added value:

- Scientific Value: The models generated allow for anticipating potential changes in the AinDraham ecosystem and provide actionable insights for territorial management, including wildfire prevention, reforestation policies, and sustainable water resource management. This approach aligns with recent studies on the application of AI in environmental management, highlighting its role in optimizing resource allocation and enhancing predictive capabilities (Rolnick et al., 2019).

- Educational Value: Students engage in a project-based learning approach that combines data collection, AI-driven modeling, and critical interpretation of results. This methodology promotes the development of interdisciplinary skills ranging from ecology to data science, including geographic information systems (GIS) and environmental ethics while reinforcing students' civic engagement and ecological awareness. Such integrative learning strategies have been shown to enhance students' understanding of complex environmental systems and foster a deeper commitment to sustainable practices (Wals et al., 2017).

DISCUSSION AND LIMITATIONS

Integrating Artificial Intelligence (AI) into environmental education, particularly through case studies like the ecological modeling of the AinDraham forest, offers significant opportunities for enhancing sustainable development education. However, this approach also presents several challenges that must be critically examined to ensure its effectiveness and ethical implementation. The reliability of AI models in environmental contexts heavily depends on the quality, resolution, and temporal consistency of the data utilized. In the case of AinDraham, satellite imagery from Sentinel-2 and climatic data from WorldClim were instrumental in identifying trends such as forest cover changes and erosion patterns.

Nevertheless, these datasets have inherent limitations, including spatial resolution constraints and infrequent updates, which can affect the accuracy of predictive models. This underscores the necessity for continuous data validation and the integration of field observations to corroborate AI-generated predictions, aligning with the findings of Reed et al. (2013), who emphasize the importance of combining modeling with empirical data collection in environmental studies.

Ethical considerations also play a crucial role in the deployment of AI in environmental education. The collection and analysis of environmental and social data raise concerns about data privacy, consent, and the potential for reinforcing existing inequalities. As highlighted by Floridi & Cowls (2019), it is imperative to approach AI applications with a framework that prioritizes transparency, accountability, and fairness. In the AinDraham project, engaging

students in discussions about environmental justice and equity not only enriched their learning experience but also fostered a deeper understanding of the ethical implications of AI technologies in real-world scenarios.

The success of AI-driven educational initiatives is also contingent upon the preparedness of educators to effectively integrate these technologies into their teaching practices. In the AïnDraham case, while students demonstrated enthusiasm and adaptability in utilizing tools like QGIS and Google Earth Engine, some educators faced challenges in mastering the technical aspects of AI applications. Holmes et al. (2019) argue that professional development programs focusing on both the technical and pedagogical aspects of AI are essential for empowering educators to leverage these tools effectively. Without adequate training and support, there is a risk that AI applications may remain underutilized or misapplied in educational settings. Access to technology remains a significant barrier, particularly in regions with limited infrastructure. In Tunisia, disparities in internet connectivity and access to computing resources can hinder the implementation of AI-based educational projects. Selwyn (2016) notes that digital inequalities can exacerbate existing educational disparities, limiting the reach and impact of innovative teaching methods.

To address this, adopting low-tech solutions, such as offline data collection tools and open-access educational resources, can help bridge the digital divide and ensure equitable access to AI-enhanced learning experiences.

Despite these challenges, the AïnDraham case study demonstrates the potential of AI to enrich environmental education by providing students with hands-on experience in data collection, analysis, and modeling. By framing AI not merely as a tool for efficiency but as a catalyst for critical thinking and ethical reflection, educators can cultivate a generation of learners who are both technologically adept and environmentally conscious. This approach aligns with the perspectives of Luckin et al. (2016), who advocate for an AI-enhanced education system that fosters inquiry, creativity, and a deep understanding of the complexities of sustainability.

In conclusion, while the integration of AI into environmental education presents numerous opportunities, it is essential to approach its implementation thoughtfully and inclusively. By addressing the technical, ethical, and infrastructural challenges identified in the AïnDraham project, educational institutions can harness the full potential of AI to advance sustainable development education and prepare students to navigate the environmental challenges of the future.

CONCLUSION

The intersection of sustainable development and artificial intelligence (AI) represents a dual transition both ecological and digital that profoundly challenges contemporary education.

AI should not be regarded merely as a technological innovation; it must be understood as a civilizational issue, whose impact depends on the values and knowledge we impart to future generations.

The pedagogical experiment conducted through the ecological modeling of the AïnDraham forest highlights AI's potential as a transformative tool in sustainability education. By combining data collection, modeling, scenario simulation, and visualization, this approach demonstrates that AI can extend beyond technical functionality to become a catalyst for curriculum innovation. It allows students to actively engage in scientific inquiry, explore complex environmental interactions, and translate abstract concepts into concrete, actionable insights. Scientifically, AI-generated models provide actionable knowledge for territorial management, support evidence-based policy-making, and illuminate strategies for addressing climate and ecological challenges.

Pedagogically, it encourages project-based learning, critical thinking, and interdisciplinary skill development, spanning ecology, data science, GIS, environmental ethics, and civic responsibility. Students not only acquire technical expertise but also cultivate an understanding of the broader societal and environmental implications of innovation. Integrating AI-driven sustainability approaches into curricula paves the way for transformative education that bridges technological innovation, civic engagement, and ecological responsibility.

However, successful implementation requires careful attention to teacher training, equitable access to resources, energy-efficient infrastructure, and transparent governance of data and models.

On a broader scale, this initiative aligns with the United Nations' 2030 Agenda and UNESCO's emphasis on sustainability education as a global priority. It also opens avenues for international collaboration through networks of "green schools," collaborative university laboratories, and transdisciplinary research projects. In this sense, the AïnDraham forest serves not only as a local experimental site but as a universal exemplar, illustrating how AI can underpin a future-oriented pedagogy that is reflective, responsible, and committed to the common good.

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