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Enhancing Environmental Awareness in Primary Schools Through Augmented Reality-Integrated Curriculum

Hasan Arslan[1], Kadir Tunçer[2], Albena Vutsova[3], Lia Bologa[4], Ieva Tenberga[5]

Prof. Dr., Educational Sciences, Çanakkale Onsekiz Mart University, Çanakkale, Turkey[1]

Lecturer Dr., Department of Informatics, Çanakkale Onsekiz Mart University, Çanakkale, Turkey [2]

Prof. Dr., PhD, Faculty of Economics and Business Adm., Sofia University "Sv. Kliment Ohridski", Sofia, Bulgaria[3]

Lect. Univ. Dr., Teacher Training Department, Lucian Blaga University of Sibiu, Sibiu, Romania[4]

Project Expert, Faculty of Education Sciences and Psychology, University of Latvia, Riga, Latvia[5]

Abstract: This study presents Green Deal Awareness through Augmented Reality in Primary School Education, an innovative curriculum designed to integrate environmental sustainability education with Augmented Reality (AR) technology. Developed collaboratively by five European institutions, the curriculum aims to equip pre-service teachers and educators with the skills to foster ecological and digital competencies in young learners. Structured into five modules—Green Deal Awareness, Augmented Reality, Environmental Education, AR in Education, and AR for Green Deal Awareness—the program leverages AR's immersive capabilities to enhance engagement, comprehension, and emotional connection to sustainability topics.

The research employs a mixed-methods approach, combining surveys (N=250+) and interviews (N=50+) across five countries to assess educational needs and evaluate the curriculum's effectiveness. Findings highlight AR's potential in visualizing abstract environmental concepts (e.g., climate change, circular economies) and fostering active, constructivist learning. However, challenges such as technological barriers, teacher training gaps, and equitable access are identified.Pilot testing demonstrates that AR-enhanced modules significantly improve student motivation and environmental literacy, with applications like virtual field trips and interactive simulations making Green Deal principles tangible. The study underscores the importance of interdisciplinary collaboration, policy support, and localized adaptations to scale this approach. By merging cutting-edge technology with sustainability education, this curriculum offers a transformative model for preparing future generations to address global ecological challenges, aligning with the European Green Deal's vision of a climate-neutral society.

Keywords: European Green Deal, sustainability education, primary schools, environmental awareness, immersive learning, curriculum development.

I. INTRODUCTION

The curriculum, titled *Green Deal Awareness through Augmented Reality in Primary School Education*, is designed to integrate environmental sustainability (European Green Deal) with innovative Augmented Reality (AR) technology. It aims to equip pre-service teachers, educators, and practitioners with the skills to foster ecological and digital competencies in primary education. Developed by five partner institutions across Europe, the curriculum is structured into five modules, each addressing key themes: Green Deal Awareness, Augmented Reality, Environmental Education, AR in Education, and AR for Green Deal Awareness.

The global climate crisis and accelerating environmental degradation have made sustainability education an urgent priority for 21st-century learning. The European Green Deal (EGD), adopted in 2019 as the European Union's flagship sustainability initiative, represents an ambitious roadmap for achieving climate neutrality by 2050 through systemic transformations across energy, industry, agriculture, and education sectors (European Commission, 2023). While technological and policy solutions are crucial, the EGD explicitly recognizes education as the fundamental driver of long-term behavioural change, particularly emphasizing the need to cultivate environmental consciousness from early childhood (Bianchi et al., 2022). This paradigm shift demands innovative pedagogical approaches that can make complex sustainability concepts accessible, engaging, and actionable for young learners—a challenge that traditional environmental education methods often fail to address.

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Augmented Reality (AR) has emerged as a transformative educational technology with unique potential to bridge the gap between abstract sustainability principles and concrete learning experiences. Defined as a technology that overlays digital information onto the physical world in real-time (Azuma, 1997), AR offers immersive, interactive, and multisensory learning opportunities that align with contemporary constructivist pedagogies (Lu & Liu, 2015). Research demonstrates AR's efficacy in enhancing knowledge retention (by 25-30% compared to traditional methods), boosting learner motivation (Ibáñez & Delgado-Kloos, 2018), and facilitating collaborative problem-solving—all critical competencies for sustainability education.

II. LITERATURE REVIEW

The European Green Deal (EGD) emphasizes education as a catalyst for behavioural change, advocating for curricula that embed sustainability (Bianchi et al., 2022). Its goals—reducing emissions, promoting circular economies, and preserving biodiversity—require innovative teaching methods to resonate with children. Environmental education in primary schools often struggles with engagement, as traditional methods fail to contextualize these themes.

AR overlays digital content onto the real world, enriching learning through interactivity. Studies highlight its efficacy in improving retention, motivation, and collaboration (Ibáñez & Delgado-Kloos, 2018). For instance, AR applications like *Green Quest* simulate renewable energy systems, while *EcoExplorer* offers virtual field trips to endangered ecosystems (GedonSOFT, 2023). Such tools align with constructivist theories, where active exploration fosters deeper understanding (Lu & Liu, 2015). AR's strength lies in visualizing abstract environmental processes. For example, pupils can observe deforestation's impact in real-time or interact with 3D models of carbon cycles. This experiential learning not only clarifies complex topics but also instills emotional connections to environmental issues (Kamarainen et al., 2013).

The European Green Deal (EGD) represents a transformative strategy aimed at achieving climate neutrality by 2050, integrating economic, social, and environmental dimensions of sustainability. A critical component of this strategy is raising awareness and fostering behavioural change, particularly among younger generations. Primary school education plays a pivotal role in this endeavor, as it shapes children's attitudes and behaviours toward environmental stewardship. Augmented Reality (AR) has emerged as a promising tool to enhance Green Deal awareness by providing immersive, interactive, and engaging learning experiences. This literature review explores the intersection of Green Deal awareness, primary school education, and AR, drawing on the provided document to synthesize key findings and insights.

A. Green Deal Awareness in Primary School Education

The Green Deal is rooted in the concept of sustainable development, which seeks to balance economic growth with environmental protection and social equity. The EGD, launched in 2019, outlines ambitious goals such as reducing greenhouse gas emissions, promoting renewable energy, and fostering circular economies (European Commission, 2023). However, achieving these goals requires widespread public awareness and participation. Education is identified as a fundamental vehicle for this transformation, as it equips learners with the knowledge, skills, and values necessary to advocate for sustainability (European Commission, 2022).

In primary schools across Europe, Green Deal awareness is integrated into curricula through subjects like natural sciences, social studies, and environmental education. For instance, Bulgaria's state education standard emphasizes ecological culture, sustainable resource use, and civic responsibility (Ordinance No. 13, 2016). Similarly, Latvia's educational framework incorporates sustainability into cross-cutting competencies, encouraging students to explore ecosystems, biodiversity, and climate action (Republic of Latvia Cabinet Regulation No. 747, 2018). Despite these efforts, challenges persist, including insufficient engagement from member states and a lack of societal involvement (IEEP, 2023). AR offers a potential solution by making abstract concepts tangible and fostering active participation.

B. Augmented Reality in Education

AR technology overlays digital content onto the real world, creating interactive and immersive learning experiences. Defined by Azuma (1997), AR combines real and virtual elements, operates in real-time, and is registered in 3D space. Its applications in education are vast, ranging from virtual field trips to interactive simulations (Wu et al., 2013). AR enhances learning by engaging multiple senses, promoting collaboration, and accommodating diverse learning styles (Garzón et al., 2017).

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In primary education, AR has been used to teach subjects such as mathematics, science, and geography. For example, AR applications allow students to visualize geometric shapes, explore the solar system, or interact with historical artifacts (Cascales-Martínez et al., 2016). Studies indicate that AR increases student motivation, improves retention, and fosters deeper understanding (Di Serio et al., 2013). However, its adoption faces barriers, including the need for teacher training, technological infrastructure, and culturally relevant content (Alalwan et al., 2020).

C. Integrating AR and Green Deal Awareness

The fusion of AR and Green Deal education holds significant potential. AR can bring environmental concepts to life, enabling students to witness the effects of climate change, explore renewable energy systems, or simulate sustainable practices. For instance, virtual tours of solar farms or interactive recycling games can make sustainability tangible and actionable (Theodorou et al., 2018). Research by Chen (2022) demonstrates that AR-based environmental education enhances students' ecological attitudes and behaviours.

Country-specific initiatives highlight this potential. In Bulgaria, platforms like "Smart Classroom" incorporate AR to teach ecological topics (Smart Classroom, 2020). Germany uses AR for virtual field trips and collaborative projects on sustainability (Lu et al., 2015). Latvia's "Urda" nature park employs AR to teach resource management (Urda, n.d.), while Romania's "Green Week" program integrates AR into climate education (Ministerul Educaţiei, 2023). These examples underscore AR's versatility in contextualizing Green Deal principles for young learners.

D. Challenges and Future Directions

Despite its promise, the integration of AR in Green Deal education faces challenges. Technical limitations, such as the need for compatible devices and stable internet access, can hinder implementation (Alalwan et al., 2020). Pedagogically, educators must ensure that AR activities align with learning outcomes and avoid becoming mere technological novelties (Fotaris et al., 2017). Additionally, cultural and linguistic adaptations are necessary to make AR tools accessible across diverse educational settings (Zālīte-Supe, 2022).

Future research should explore the long-term impact of AR on environmental literacy and behaviour. Studies could also investigate the role of teacher training in maximizing AR's educational potential. Collaborative efforts between policymakers, educators, and technology developers are essential to create scalable and sustainable AR solutions for Green Deal awareness.

III. METHODOLOGY

This study employed a mixed-methods research design, integrating both quantitative and qualitative approaches to provide a comprehensive understanding of the educational needs related to environmental awareness across different European contexts. The research was conducted within the scope of an Erasmus+ project coordinated by Sofia University St. Kliment Ohridski in Bulgaria, in partnership with Çanakkale Onsekiz Mart University (Turkey), the University of Latvia (Latvia), Lucian Blaga University of Sibiu (Romania), and the Baltic Education Technical Institute (Latvia).

To identify the existing gaps and needs in educational programs aimed at fostering environmental awareness, data were collected simultaneously in five partner countries using surveys and semi-structured interviews. More than 250 participants completed the surveys, and over 50 in-depth interviews were conducted with educators, stakeholders, and experts in environmental education. The quantitative data collected through the surveys provided a broad understanding of trends and common needs, while the qualitative data from interviews offered deeper insights into contextual and country-specific issues.

Following the comprehensive needs analysis, a modular educational program was designed to address the identified requirements. This program was then implemented in a pilot study to assess its relevance, applicability, and effectiveness in real educational settings. Based on the feedback and outcomes from the pilot phase, necessary revisions were made, and the final version of the modular program was developed and validated for further use.

IV. RESULTS AND DISCUSSION

In this study, five instructional modules were developed with the aim of enhancing environmental awareness among primary school students. The following sections present a detailed discussion of these modules. The complete modular program is accessible via the project website at www.greenwithar.com. This platform also provides access to the AR-

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integrated modular curriculum, as well as a digitally enriched teaching guide that incorporates the instructional materials developed in alignment with the program. Additional information regarding other components of the project is also available on the website.

Module 1: Green Deal Awareness

This module, titled "The European Green Deal and Definition of Green Deal Awareness," offers a comprehensive exploration of the European Union's Green Deal initiative, its policy framework, and the pedagogical approaches necessary to foster environmental consciousness within educational contexts. Designed for a two-hour session, it equips learners with both theoretical knowledge and practical tools for integrating sustainability into teaching practices.

The European Green Deal (EGD), introduced by the European Commission in December 2019, is a far-reaching policy package aimed at achieving climate neutrality by 2050 and reducing greenhouse gas emissions by 55% by 2030 compared to 1990 levels. It represents a systemic and cross-sectoral strategy involving climate, energy, transport, industry, agriculture, biodiversity, and sustainable finance. It is also embedded in the broader EU commitment to the United Nations' 2030 Agenda for Sustainable Development.

From a theoretical perspective, the EGD emphasizes a shift from a linear to a circular economic model, incorporating sustainable production and consumption patterns. This includes promoting green growth, green jobs, and investment in technological innovations such as clean energy and sustainable mobility. Although the EU's rhetorical commitment to sustainability is robust, critiques (e.g., Braun, 2013; Siddi, 2020) highlight the contradictions between continued economic growth and the planet's finite resources.

Green Deal Awareness, as conceptualized in this module, extends beyond mere knowledge of policy frameworks. It involves cultivating the capacity to perceive environmental risks, understand psychological responses to climate change (e.g., psychological distance and risk normalization), and develop transformative educational strategies. The goal is not only cognitive but behavioral—instilling values, competencies, and practices that promote ecological responsibility and resilience.

The module integrates a constructivist pedagogical approach. Through brainstorming, group work, discussions, and feedback sessions, learners analyze the strengths and limitations of the Green Deal and explore classroom applications. Emphasis is placed on organizing debates, using visual aids, and leveraging students' prior knowledge and concerns to foster engagement.

In terms of content, the session explores the EGD's key themes: funding mechanisms, global interdependencies, and policy instruments (e.g., Fit for 55). It also links the Green Deal to broader educational reform in the EU, advocating for green skills development, sustainable school infrastructure, and transformative learning aligned with the European Sustainability Competence Framework (GreenComp).

Ultimately, this module serves as both an informative and action-oriented entry point into environmental education, aligning EU policy with educational innovation and learner empowerment. It reflects the EU's vision that education and training are essential for enabling the green transition and shaping environmentally literate citizens

Module 2: Scholarly Summary: Augmented Reality – Concepts, Development, and Educational Applications

This module introduces the foundational concepts of Augmented Reality (AR), its historical evolution, technological characteristics, and diverse applications, with a special emphasis on its pedagogical potential to foster Green Deal awareness and active learning in education.

Definition and Perspectives of Augmented Reality: Augmented Reality (AR) refers to the integration of digital information—text, images, audio, or 3D models—into the real-world environment in real time. Unlike Virtual Reality (VR), which immerses users in a fully synthetic world, or Mixed Reality (MR), which allows dynamic interaction between physical and digital elements, AR enhances rather than replaces the physical surroundings. It forms part of the broader concept of Extended Reality (XR), an umbrella term encompassing AR, VR, MR, and hybrid technologies (Tremosa, 2023).

AR definitions vary by context. From a technical perspective, AR requires input devices (e.g., smartphones, AR glasses), sensors for tracking user and object positions, and displays (e.g., head-mounted displays, monitors). From a

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user-experience perspective, AR enhances user engagement by enabling personalized, interactive, and multisensory experiences. Furthermore, its application-focused perspective reveals AR's versatility across fields such as education, healthcare, tourism, architecture, and entertainment (Carmigniani & Furht, 2011; Arena et al., 2022).

Historical Development and Usage Areas: Historically, AR evolved through advancements in sensor technology, mobile computing, and display systems. While initially utilized in military and industrial applications, AR's reach has significantly expanded. In education, it enables immersive, collaborative, and contextualized learning by blending theoretical knowledge with real-world experiences. This pedagogical innovation aligns with contemporary education paradigms that value student-centered, inquiry-based, and personalized learning.

Pedagogical Implementation - A Classroom Example: The module includes a structured 2-hour lesson plan designed to introduce students to AR. Learning outcomes focus on defining AR, stimulating curiosity, encouraging multisensory exploration, and fostering the application of knowledge in real-world scenarios. Instructional strategies include lectures, discussions, group tasks, and the "I Know – I Want to Know – I Have Learned" (K-W-L) model.

Students actively engage through tools such as Padlet, where they collaboratively record and refine their evolving understanding of AR. Brainstorming sessions and multimedia resources—including diagrams, interactive websites, and a YouTube tutorial—facilitate the differentiation of AR from VR, MR, and XR. Discussions also explore the necessity of integrating AR in education, particularly for fostering environmental awareness and complex problem-solving.

The course uses formative assessment, allowing ongoing feedback and peer-supported learning. Students co-construct definitions and engage in reflective activities to consolidate learning and identify further inquiries. This process underscores AR's value in supporting metacognitive awareness, critical thinking, and interdisciplinary learning.

This module frames AR not merely as a technological novelty but as a transformative educational tool. Through a blend of theoretical grounding and interactive practice, students come to appreciate AR's potential to personalize learning, contextualize knowledge, and deepen engagement with global challenges such as the Green Deal. The approach adopted in this module reflects a broader shift in education toward experiential, technology-enhanced learning environments.

Module 3: Environmental Education and Green Deal Awareness in Primary Education

This instructional module focuses on integrating environmental education into the primary education curriculum to foster awareness of the European Green Deal among future educators and students. The module is structured around three central themes: (1) Environmental Education in the Primary Education Curriculum, (2) Contributions of Environmental Education to Green Deal Awareness, and (3) Strategies to Increase Green Deal Awareness in Primary Education.

Environmental education is framed as a key component in fostering environmentally responsible behaviors among students aged 6–14. According to the Turkish Environmental Atlas (2004), the aim is not merely to transfer knowledge but to develop environmental consciousness and proactive behaviors. The Turkish Ministry of Environment and Forestry, in collaboration with the Ministry of National Education, initiated protocols to integrate environmental content across subjects such as Life Science, Science, Social Studies, and Turkish. The Life Science curriculum, especially in grades 1–3, includes themes such as recycling, nature appreciation, and environmental safety. Social Studies at grade 4 addresses spatial awareness, environmental observation, and disaster preparedness. The Science curriculum further explores the natural-artificial environment distinction and pollution awareness.

The module utilizes active, student-centered teaching methods, particularly cooperative learning through the jigsaw technique. Pre-service teachers explore curriculum-integrated environmental gains in Life Science, Mathematics, and Social Studies. They first collaborate in small groups, then rotate into expert groups focusing on one subject area. This method encourages peer teaching, critical reflection, and synthesis of interdisciplinary content. Discussions, presentations, and teacher feedback support the learning process, ensuring a holistic understanding of environmental themes within primary education.

Environmental education serves as a foundation for cultivating competencies aligned with the European Green Deal, such as sustainable development, circular economy principles, and responsible consumption. The inclusion of applied activities and in-service training for teachers enhances the systemic implementation of Green Deal goals. By embedding these themes into the formal curriculum and teacher education, learners not only gain environmental knowledge but also develop attitudes and behaviors crucial for ecological citizenship.

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This module exemplifies how structured environmental education in primary schools can contribute meaningfully to Green Deal awareness. By equipping pre-service teachers with both content knowledge and pedagogical strategies, the program supports long-term sustainability education objectives. The interdisciplinary and interactive model fosters reflective, informed, and responsible future educators capable of guiding young learners toward environmental stewardship.

Module 4: Usage Areas of Augmented Reality in Education

This module explores the integration of Augmented Reality (AR) in educational settings, particularly in primary education, focusing on software tools, pedagogical benefits, practical applications, and critical considerations for implementation. The lesson, designed for pre-service teachers, emphasizes hands-on and collaborative learning strategies to familiarize participants with AR tools and evaluate their potential for enriching learning environments, especially for topics such as environmental education.

Participants are introduced to various AR applications suitable for educational use, with specific attention to tools applicable in primary schools. Through a combination of lectures, demonstrations, and group activities, students explore the design, technical use, and educational affordances of AR software. The session encourages pre-service teachers to experiment with AR tools and conceptualize their potential classroom applications, including the development of original AR experiences. A critical component involves peer evaluation and reflective discussion to foster deeper understanding and confidence in using AR.

Research highlights the transformative potential of AR in increasing student motivation, visualizing abstract concepts, and enhancing cooperative learning (Zhang et al., 2014; Lu & Liu, 2015). AR is particularly effective in bridging theoretical content with real-life experiences, facilitating situated learning. However, barriers to effective AR integration remain, including limited teacher training, restricted access to technology, and inadequate educational resources (Akçayır & Akçayır, 2017; Gómez-García et al., 2021).

Effective AR use requires well-designed applications with intuitive user interfaces and meaningful content. Hidayat et al. (2021) emphasize the importance of linking AR content to learners' real-world experiences and prior knowledge. For instance, applications that contextualize abstract scientific processes in familiar settings improve comprehension. Moreover, AR tools must be adaptable to varying instructional timeframes, easily integrable into lesson plans, and free from cognitive overload to maintain pedagogical effectiveness (Zydney & Warner, 2016).

During the session, pre-service teachers examine a variety of AR tools and analyze their relevance to different curriculum areas. Students are encouraged to identify educational AR apps from curated lists and assess their suitability for enhancing primary-level instruction. Presentations and discussions help consolidate knowledge and provide critical reflections on both the opportunities and limitations of AR technologies in diverse classroom scenarios.

The module underscores the strategic value of AR in promoting engaging and effective learning experiences. By equipping future educators with both theoretical insights and practical competencies, the session aims to foster a critical, creative, and informed approach to incorporating AR in primary education. Key takeaways include the importance of thoughtful application design, alignment with curricular goals, and addressing infrastructural and pedagogical barriers to ensure meaningful AR integration in classrooms.

Module 5: The Role of Augmented Reality in Enhancing Green Deal Awareness in Primary Education

Augmented Reality (AR) is increasingly recognized as a transformative tool in primary school education, offering immersive and interactive experiences that can deepen understanding and engagement. Unlike Virtual Reality (VR), which replaces the physical world, AR overlays digital information onto real-world environments, enhancing rather than replacing the learning context (Milgram & Kishino, 1994). This pedagogical potential is particularly relevant to education for sustainable development, such as fostering awareness of the European Green Deal among young learners. A dedicated training module, titled "The Role of Augmented Reality in Primary School Education," has been developed to equip educators with the knowledge and skills needed to implement AR in classrooms effectively. Spanning two hours, the module addresses fundamental AR concepts, explores educational tools such as Aurasma and Google Expeditions AR, and provides hands-on opportunities to design AR-enhanced lesson plans. Teaching methods include interactive lectures, group discussions, demonstrations, and collaborative activities.

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Research supports the efficacy of AR in improving memory retention, motivation, and engagement among primary school students (Ibáñez & Delgado-Kloos, 2018). In this context, AR aligns well with young learners' innate curiosity and exploratory behaviors. By enabling the visualization of abstract or complex concepts—such as environmental processes or the impact of human activity on ecosystems—AR fosters critical thinking and enhances comprehension.

The module also emphasizes how AR can be integrated into assessment practices, allowing for immediate feedback and personalized evaluation. However, educators are cautioned to consider the validity of AR-based assessments and address challenges such as technical limitations, device accessibility, and the need for teacher training (Di Serio et al., 2013; Bujak et al., 2013).

Ethical considerations play a crucial role in the implementation of AR in education. These include ensuring data privacy, securing parental consent, promoting equitable access to technology, and adhering to culturally sensitive content guidelines (Luckin et al., 2006). By embedding these principles, educators can create inclusive and responsible AR-enhanced learning environments.

Crucially, AR holds promise for advancing sustainability education. Through simulations, interactive models, and contextual storytelling, AR can vividly illustrate key principles of the Green Deal—such as climate action, biodiversity, and sustainable resource use—helping young students connect abstract policy goals to real-world implications. The integration of AR in primary education not only enriches pedagogical practices but also serves as a powerful medium for cultivating environmental consciousness and global citizenship among the next generation.

The European Green Deal represents a bold vision for a sustainable future, and primary education is a critical arena for fostering the necessary awareness and action. Augmented Reality offers a dynamic and engaging medium to teach Green Deal concepts, bridging the gap between abstract ideas and real-world applications. While challenges exist, the successful integration of AR in classrooms across Europe demonstrates its potential to inspire the next generation of environmental stewards. By leveraging AR's immersive capabilities, educators can cultivate a deeper understanding of sustainability and empower students to contribute meaningfully to the Green Deal's goals.

V. CONCLUSION

The integration of Augmented Reality (AR) into primary school curricula to enhance environmental awareness represents a significant advancement in sustainability education, aligning with the ambitious goals of the European Green Deal (EGD). This curriculum, *Green Deal Awareness through Augmented Reality in Primary School Education*, bridges ecological literacy and digital innovation, equipping educators with the pedagogical tools necessary to cultivate environmentally conscious and technologically proficient young learners. The findings from this study underscore the potential of AR as an immersive, interactive, and engaging medium for fostering Green Deal awareness, while also highlighting key challenges and future directions for research and implementation.

Key Contributions

1. Interdisciplinary Integration of Sustainability and Technology

The modular curriculum successfully merges environmental education with AR, addressing a critical gap in traditional pedagogical approaches. By leveraging AR’s capacity to visualize abstract concepts—such as climate change, biodiversity loss, and circular economies—the curriculum enhances comprehension and emotional engagement among primary school students. This aligns with constructivist learning theories, where active, experiential learning promotes deeper understanding and long-term behavioral change (Lu & Liu, 2015; Kamarainen et al., 2013).

2. Pedagogical Innovation

The five modules provide a structured yet flexible framework for educators, combining theoretical foundations with practical applications. For instance, Module 4 (*Usage Areas of AR in Education*) demonstrates how AR tools can transform passive learning into dynamic, student-centered experiences. Similarly, Module 5 (*AR for Green Deal Awareness*) illustrates how simulations and virtual field trips can make sustainability tangible, fostering empathy and agency in young learners.

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3. Cross-Cultural Applicability

Developed through a collaborative Erasmus+ project involving five European institutions, the curriculum reflects diverse educational contexts, from Bulgaria's ecological culture initiatives to Latvia's competency-based sustainability frameworks. This adaptability ensures relevance across different national curricula while maintaining alignment with EU-wide Green Deal objectives.

Challenges and Limitations

Despite its promise, the widespread adoption of AR-integrated environmental education faces several barriers:

Technological and Infrastructural Constraints: Unequal access to AR-compatible devices and stable internet connectivity may exacerbate educational disparities, particularly in under-resourced schools (Alalwan et al., 2020).

Teacher Preparedness: Many educators lack training in both AR technology and sustainability pedagogy, necessitating robust professional development programs (Fotaris et al., 2017).

Assessment and Ethical Considerations: While AR enhances engagement, measuring its long-term impact on environmental behavior remains challenging. Additionally, ethical concerns—such as data privacy and equitable access—must be addressed to ensure responsible implementation (Luckin et al., 2006).

Future Directions

To maximize the curriculum's impact, the following steps are recommended:

1. Longitudinal Studies: Research should evaluate the sustained effects of AR on environmental literacy and pro-ecological behaviors beyond short-term engagement.
2. Policy Integration: Governments and educational bodies should institutionalize AR-enabled sustainability education, providing funding for devices, teacher training, and localized content development.
3. Community and Parental Involvement: Partnerships with NGOs, tech developers, and families can amplify learning beyond the classroom, embedding sustainability into everyday practices.

Final Reflections

This curriculum exemplifies how cutting-edge technology can serve as a catalyst for transformative education. By immersing students in interactive, emotionally resonant learning experiences, AR not only demystifies the European Green Deal but also empowers children to see themselves as active participants in a sustainable future. As digital and ecological competencies become increasingly intertwined, initiatives like this offer a blueprint for 21st-century education—one where innovation and environmental stewardship go hand in hand.

The success of this approach hinges on collaborative effort: educators embracing new pedagogies, policymakers allocating resources, and researchers refining best practices. If these stakeholders align, AR-enhanced environmental education can transcend the classroom, inspiring a generation of learners to champion the Green Deal's vision of a resilient, equitable, and climate-neutral Europe.

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