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Integrating Advanced Technologies in Education: Empowering Youth for a Sustainable Future through New Literacies

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Abstract/Izvleček
The quasi-experimental study explores how contemporary technologies, such as artificial intelligence and humanoid robots, enhance sustainability education for pre-service teachers. The study, involving 112 participants, assessed the effectiveness of these technologies compared to traditional methods in improving sustainability literacy. Pre- and post-tests revealed significant improvements in understanding sustainability concepts, with humanoid robots increasing response variability. Results highlight the technologies' ability to engage educators in sustainability topics, promoting new literacies critical for addressing environmental challenges.

Vključevanje naprednih tehnologij v izobraževanje: opolnomočenje mladih za trajnostno prihodnost s pomočjo novih pismenosti
Kvazi-eksperimentalna študija raziskuje, kako sodobne tehnologije, kot sta umetna inteligenca in humanoidni roboti, izboljšujejo izobraževanje za trajnostni razvoj pri bodočih učiteljih. Študija, v kateri je sodelovalo 112 udeležencev, je ocenjevala učinkovitost teh tehnologij v primerjavi s tradicionalnimi metodami pri izboljševanju trajnostne pismenosti. Predtest in potest sta pokazala pomembne izboljšave v razumevanju trajnostnih konceptov, pri čemer so humanoidni roboti povečali raznolikost odzivov. Rezultati poudarjajo potencial sodobnih tehnologij za vključevanje učiteljev v trajnostne teme ter spodbujajo nove pismenosti.

Keywords:
advanced technologies, digital competence, humanoid robots, sustainability education, teacher training.

Ključne besede:
digitalne kompetence, humanoidni roboti, napredne tehnologije, trajnostno izobraževanje, usposabljanje učiteljev.

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Introduction

The rise of advanced technologies, such as artificial intelligence (AI) and humanoid robots (HRs) has reshaped education, in some contexts prompting global adaptations (Timotheou et al., 2023) while shaping a sustainable future. This article explores how technologies like ChatGPT and HRs empower youth to engage in sustainability initiatives and address environmental challenges. It assesses how effective these tools are compared to traditional methods in fostering environmental awareness, focusing on future teachers. The study also identifies essential new literacies for leveraging these technologies to promote sustainability.
The research questions are as follows:

- RQ1: How do advanced technologies compare to traditional methods in enhancing youth awareness of environmental sustainability?
- RQ2: How do learning methods influence variability in shaping and transmitting sustainable values, particularly among future teachers?
- RQ3: What new literacies, knowledge, and skills are essential for young educators to effectively promote sustainability using advanced technologies?

The paper is structured as follows: Section 2 reviews the literature on AI, HRs, and sustainability education; Section 3 outlines the methodology; Section 4 presents results, and Section 5 discusses findings and implications for future research.

Literature Review

Advanced Technologies in Sustainability Education

The rapid development of digital technology has transformed everyday reality, enabling people to connect, access information, and express themselves in diverse ways. Digital technology is now integral to everyday life, including AI integrated into contemporary communication processes (Starc and Komninos, 2023). AI and HRs in sustainability education can enhance learning outcomes and understanding of environmental challenges, aiding in achieving Sustainable Development Goals (SDGs) (Vinuesa et al., 2020). To maximize the benefits of AI and HRs in environmental education (EE) requires an understanding of how they support learning.

They offer dynamic, interactive experiences, making abstract concepts tangible and adapting in real time (Xu and Ouyang, 2022). Integrating these tools into the curriculum promotes a multidisciplinary approach, combining computer science, environmental studies, and critical thinking (Mishra et al., 2021).

Integrating AI-driven platforms like ChatGPT and HR into EE can improve sustainability understanding and introduce new paradigms in education. Their interactivity and personalization encourage young people to develop innovative solutions to environmental issues, strengthening their role as sustainability innovators (Niu et al., 2024; Okulich-Kazarin et al., 2024). Holistic integration of these tools into educational practices is critical, rather than simply adding them to existing methods.

Literacies for Integrating Advanced Technologies in Education

Education for various forms of literacy has become essential in preparing individuals to engage in planning, problem solving, and informed decision-making. This is particularly important as literacy is essential for responsible and effective technology use (Lemut Bajec, 2023). Emerging forms of literacy are increasingly essential for addressing technological and environmental challenges. These new literacies involve skills for understanding and using advanced technologies, empowering youth to create sustainable strategies. They extend beyond traditional definitions, incorporating multimodal forms of expression that support lifelong learning and global collaboration (Barut Tugtekin and Koc, 2020).

New literacies include the ability to critically evaluate and use diverse information and communication technologies, preparing learners for a dynamic technological environment. This evolution demands adapting educational methods, environments, and assessment strategies to meet contemporary needs (Reilly, 2009). Digital technologies, increasingly prominent in education, can support more engaging and efficient learning resources (Sila and Klančar, 2024). As advancements redefine the skills needed, educators must equip students with tools fostering adaptability, problem-solving, and critical thinking.

The European Commission's Digital Competence Framework for Citizens (DigComp) provides a comprehensive outline of essential digital skills, including information literacy, communication, content creation, safety, and problem-solving (Vuorikari et al., 2022).

These competences are key to preparing learners for the challenges of the digital world. Advanced technologies like AI and HRs can make learning more accessible, engaging, and globally relevant (Relmasitra et al., 2023).

Advanced Technologies in Environmental Education

Advanced technologies, particularly AI and HRs, offer innovative tools for fostering youth engagement in sustainable development. By supporting inquiry-based and problem-solving approaches, these technologies may enhance environmental awareness and responsibility (Chen et al., 2023; Hajj-Hassan et al., 2024). Integrating these tools with EE promotes a holistic understanding of the interconnection between technology and sustainability (Bonnett, 2019).

Personalized, learner-centred methods foster individual engagement and social skills but may limit broader social interactions and collective environmental consciousness (Aberšek, 2018; Aberšek et al., 2014). Emotional intelligence, a key factor, enables individuals to align behaviours with sustainability principles, fostering self-awareness and responsibility (Herič et al., 2019; Oe et al., 2022).

Young people, 30% of the global population, are vital to achieving SDGs. Despite this, they are often excluded from the decisions shaping their future (Omotosho et al., 2023). Integrating sustainability into education and preparing future educators are both essential for building long-term responsibility (Robinson et al., 2019).

Positive attitudes towards sustainability and technology-enhanced learning promote responsibility, participation in initiatives, and effective technology use (Kerneža and Zemljak, 2023; Kougias et al., 2023). Global frameworks like The 2030 Agenda for Sustainable Development (UNESCO, 2015) and The Berlin Declaration on Education for Sustainable Development (2021) stress integrating digital and green technologies into education to promote critical thinking and sustainability values. Society 5.0 also highlights technology's role in a sustainable future (Deguchi et al., 2020).

Materials and Methods

This section outlines the methodology of the study, providing a comprehensive overview of the research design, participants, measures, and data analysis methods used to explore sustainability education.

Study Participants and Procedure

The sample was purposively selected with partial random allocation. Participants included pre-service teachers aged 19–24 enrolled in the Elementary Education program at the faculty of education of one of the Slovenian universities. In Slovenia, pre-service teachers are university students in initial teacher education programs, combining subject specific knowledge, pedagogy, and practical training, who have not yet entered full-time teaching employment, comparable to initial teacher training in other European countries. These future educators were chosen for their key role in shaping sustainable educational strategies. Of 112 initial participants, 95 completed the study; 17 withdrew due to lack of interest or uncertainty regarding integrating new technologies.

A quasi-experimental design (Cooper, 2009) integrated advanced technologies into research-based sustainability learning. Participants first answered the question: "How can I contribute to improving environmental sustainability?" They then engaged in group work to explore the question, while the control group pursued unrelated activities.

Participants were divided into seven groups, each further split into pairs or trios for 15-minute exploration tasks using different methods (Table 1).

Table 1

Participant Allocation by Research Method with Detailed Group Instructions

Research Method	Group Tasks	N (groups/ participants)
ChatGPT 3.5*	Used ChatGPT for questions, ideas, and feedback to enhance sustainability efforts. Participants were trained in chatbot usage (Kerneža, 2023).	6/17
HR*	Operated an AlphaMini robot with ChatGPT to explore sustainability topics; trained for effective operation (Kerneža, 2023).	6/17
Google**	Applied Internet Reciprocal Teaching method to verify sources and compare sustainability views (Leu et al., 2008), as practiced in coursework.	6/17
School Library Books	In-depth study using library books.	5/15
Frontal Teaching	Lecture on theoretical foundations of sustainability.	6/17
Peer Discussion	Shared experiences and explored sustainability collaboratively.	6/15
Control Group	Unrelated activities.	6/15

The AlphaMini HR with ChatGPT integration used four AI models–speech synthesis, speech recognition, ChatGPT integration, and voice activity recognition– allowing Slovenian-language integration. This created interactive, accessible discussions on sustainability, promoting critical thinking.

After completing their tasks, participants revisited the initial question to reflect on how the intervention influenced their sustainability perspectives. These reflections were central for evaluating the impact of each method.

The study used systematic observations based on the Digital Competence Framework for Citizens (DigComp) (Vuorikari et al., 2022). Researchers documented 21 competences observed during participants' work with different methods, analysing how knowledge, skills, and attitudes were applied. Results were organized into tables for clarity.

Measures

Data collection involved written answers to a single open-ended question before and after the intervention. Responses were coded into thematic categories from prior research and pilot testing:

- Carbon footprint reduction (public transport, walking, cycling, reducing car usage, use of electric vehicles).
- Sustainable usage and recycling (recycling of waste, use of products for multiple uses, reducing plastic usage, buying second-hand clothes).
- Resource conservation (saving water and electricity, turning off lights, turning off the tap during tooth brushing).
- Sustainable food and agriculture (buying locally produced food, growing one's own food, using natural fertilizers, reducing meat consumption).
- Awareness and education (educating others about sustainability, training on sustainability topics, participating in cleaning actions, supporting sustainable organizations).
- Energy efficiency and renewable sources (using renewable energy sources, energy-efficient devices, digitization to reduce paper usage).
- Sustainable waste management (composting, proper waste segregation, reducing food waste).

Coded responses were analysed for common themes and variations, assessing the effects of learning methods on sustainability awareness.

Competences were classified as either "fundamental" (developed in analogue settings) or "comprehensive" (aligned with DigComp 2.2 (Vuorikari et al., 2022)). Table 2 shows the knowledge, skills, and attitudes observed.

Table 2
*Knowledge, Skills and Attitudes According to Key Components of Digital Competence**

Information and data literacy	Communication and collaboration	Digital content creation	Safety	Problem solving
1–3	4–9	10–13	14–17	18–21

*Note. Specific knowledge, skills and attitudes are numbered to show the results in Table 11. The competences are as follows: 1 – Browsing, searching, and filtering data, information and digital content; 2 – Evaluating data, information and digital content; 3 – Managing data, information and digital content; 4 – Interacting through digital technologies; 5 – Sharing through digital technologies; 6 – Engaging in citizenship through digital technologies; 7 – Collaborating through digital technologies; 8 – Netiquette; 9 – Managing digital identity; 10 – Developing digital content; 11 – Integrating and re-elaborating digital content; 12 – Copyright and licenses; 13 – Programming; 14 – Protecting devices; 15 – Protecting personal data and privacy; 16 – Protecting health and well-being; 17 – Protecting the environment; 18 – Solving technological problems; 19 – Identifying needs and technological responses; 20 – Creatively using digital technologies; 21 – Identifying digital competence gaps.

Data Analysis

Data were anonymized and stored securely to maintain confidentiality and ethical standards. Responses were analysed using descriptive coding (Saldana, 2009), redefined iteratively. Codes were transformed into numerical scores representing the number of distinct categories mentioned per participant in pre- and post-tests. After checking normality and variance homogeneity, the assumptions for parametric analysis were met, allowing repeated measures ANOVA.

Scores served as the dependent variable, enabling comparison of pre–post challenges across methods. Greenhouse–Geiser corrections were applied for sphericity violations (Bauer and Bai, 2018) and Bonferroni adjustments for multiple comparisons.

Thematic analysis identified trends and unique literacy applications; quantification included frequency analysis and cross-tabulation to link competences with methods.

Results

This section presents the findings of the study, highlighting the effects of various learning methods on participants' understanding and application of environmental sustainability concepts.

Comparative Analysis of Pretest and Post-test Scores Across Learning Methods

The impact of different learning strategies on participants' understanding of environmental sustainability was assessed through pretest and post-test scores. Using repeated measures ANOVA, this study compared the effectiveness of contemporary technologies and traditional approaches. The results are summarized in Table 3.

Table 3

Mean Scores and Standard Deviations by Learning Method for Pretest and Post-test Results

Test	Source of learning	Mean	Std. Deviation	Min	Max	N
Pretest	ChatGPT	4.00	.756	3	5	15
	HR	4.31	1.195	3	7	16
	Google	4.36	1.598	2	8	14
	Books	3.91	1.044	2	5	11
	Peer Discussion	3.50	1.834	1	8	12
	Frontal Teaching	3.60	1.404	2	6	15
	Control Group	4.50	1.834	2	7	12
	Total	4.03	1.410	1	8	95
Post-test	ChatGPT	9.93	2.915	6	18	15
	HR	11.81	6.921	6	30	16
	Google	11.29	5.165	6	24	14
	Books	6.64	2.942	2	12	11
	Peer Discussion	7.17	2.980	3	14	12
	Frontal Teaching	8.60	4.579	4	19	15
	Control Group	5.50	2.780	2	12	12
	Total	8.95	4.850	2	30	95

The repeated measures ANOVA, corrected with Greenhouse–Geiser adjustments, revealed statistically significant changes between pre- and post-test scores across all groups ($F(36.218, 8.697) = 26{,}938$, $p < .001$), indicating improvement across all methods. Standard deviations varied notably, especially in the HR ($SD = 6.921$) and Google ($SD = 5.165$) groups, showing higher post-intervention variability. While the Bonferroni post-hoc test showed no statistically significant differences between groups ($p > .05$), a borderline difference appeared between the HR group and the control group ($p = .05$). Given the conservativeness of Bonferroni adjustments, small but meaningful differences may not have been detected (Asan and Soyer, 2022).

Effect of Learning Methods on Response Variability

This section explores differences in variability across specific sustainability categories, noting the statistical significance does not necessarily indicate practical or pedagogical superiority.

Carbon Footprint Category

ANOVA results indicated statistically significant differences between learning methods ($F(6, 88) = 2.607$, $p = .023$) and a significant intercept ($F(1, 88) = 224,565$, $p < .001$). The R2 value of 3.81% indicates that learning method explained only a small portion of variability, suggesting other contributing factors. Detailed results are presented in Table 4.

Table 4

Mean Scores and Standard Deviations by Learning Method for Carbon Footprint Variability

Test	Method	Mean	Std. Deviation	Min	Max	N
Pretest	ChatGPT	1.13	.352	1	2	15
	HR	.69	.602	0	2	16
	Google	1.21	.802	0	3	14
	Books	1.55	1.215	0	4	11
	Peer Discussion	.75	.622	0	2	12
	Frontal Teaching	1.00	.000	1	1	15
	Control Group	.83	.718	0	2	12
Post-test	ChatGPT	1.20	.414	1	2	15
	HR	.69	.602	0	2	16
	Google	1.36	.929	0	3	14
	Books	1.64	1.362	0	4	11
	Peer Discussion	.92	.515	0	2	12
	Frontal Teaching	1.20	.414	1	2	15
	Control Group	.83	.718	0	2	12

A post-hoc Tukey HSD test revealed a significant difference between the HR and books groups (MD = -.90, SE = .270, $p = .020$, 95% CI [-1.72, -.09]). No other pairwise comparison showed statistically significant differences.

Sustainable Usage and Recycling

ANOVA revealed a statistically significant intercept ($F(1, 88) = 233.426$, $p < .001$) but no significant differences between methods ($F(6, 88) = 1.752$, $p = .118$; R2 = 10.7%).

Table 5
Mean Scores and Standard Deviations for Sustainable Usage and Recycling

Test	Method	Mean	Std. Deviation	Min	Max	N
Pretest	ChatGPT	1.27	1.100	0	3	15
	HR	2.12	.719	1	3	16
	Google	1.36	.633	0	2	14
	Books	1.36	1.286	0	4	11
	Peer Discussion	1.25	1.422	0	5	12
	Frontal Teaching	1.07	.961	0	3	15
	Control Group	1.58	1.240	0	3	12
Post-test	ChatGPT	2.60	1.352	1	5	15
	HR	2.63	.885	1	4	16
	Google	3.71	1.326	1	6	14
	Books	1.73	1.191	0	4	11
	Peer Discussion	2.00	2.045	0	7	12
	Frontal Teaching	2.00	1.813	0	5	15
	Control Group	1.58	1.240	0	3	12

While some post-test mean differences were notable – for example Google scored higher than books or frontal teaching – these differences were not statistically significant (Table 5). This suggests that, for this category, method choice had limited measurable impact on outcomes.

Resource Conservation

ANOVA showed significant differences between learning methods ($F(6, 88) = 3.568$, $p = .003$) and a statistically significant intercept ($F(1, 88) = 201.338$, $p < .001$) with R2 = 19.6% indicating a moderate effect of method choice (Table 6).

Post-hoc Tukey HSD indicated a significant difference between the HR and Books groups (MD = -.90, SE = .020, 95 % CI [-1.72, -.09]). Other pairwise comparisons were not significant, suggesting that while HR stood out compared to Books, no other clear differences emerged among the remaining methods.

Table 6
Mean Scores and Standard Deviations by Learning Method for Resource Conservation Variability

Test	Method	Mean	Std. Deviation	Min	Max	N
Pretest	ChatGPT	1.13	.834	0	2	15
	HR	.31	.602	0	2	16
	Google	.36	.497	0	1	14
	Books	.45	.522	0	1	11
	Peer Discussion	.50	.522	0	1	12
	Frontal Teaching	.73	.458	0	1	15
	Control Group	.83	.718	0	2	12
	ChatGPT	1.73	.884	0	3	15

	HR	1.69	1.138	0	4	16
	Google	.93	.616	0	2	14
Post-test	Books	.64	.505	0	1	11
	Peer Discussion	.83	.389	0	1	12
	Frontal Teaching	1.27	.704	0	2	15
	Control Group	.83	.718	0	2	12

Sustainable Food and Agriculture

ANOVA showed a significant intercept (F(1, 88) = 38.578, $p < .001$), confirming the overall relevance of the model in this category, but no statistically significant differences between methods (F(6, 88) = 1.110, $p = .363$; R2 = 7.04%), indicating a limited influence by instructional approach.

Table 7

Mean Scores and Standard Deviations by Learning Method for Sustainable Food and Agriculture Variability

Method		Pretest		Post-test		
Test	Method	Mean	Std. Deviation	Min	Max	N
Pretest	ChatGPT	.20	.561	0	2	15
	HR	.00	.000	0	0	16
	Google	.14	.535	0	2	14
	Books	.18	.405	0	1	11
	Peer Discussion	.17	.389	0	1	12
	Frontal Teaching	.27	.458	0	1	15
	Control Group	.42	.515	0	1	12
Post-test	ChatGPT	.60	.737	0	2	15
	HR	.13	.342	0	1	16
	Google	.57	1.016	0	3	14
	Books	.82	.874	0	3	11
	Peer Discussion	.33	.651	0	2	12
	Frontal Teaching	.67	.816	0	2	15
	Control Group	.42	.515	0	1	12

The detailed means and standard deviations, as presented in Table 7, show minimal variation attributable to method, suggesting that improvements in this category may be driven more by individual motivation or prior knowledge than by the specific instructional strategy.

Awareness and Education

ANOVA revealed a significant intercept (F(1, 88) = 73.603, $p < .001$), reinforcing the relevance of the model in assessing awareness and education, with differences between methods approaching statistical significance (F(6, 88) = 2.037, $p = .069$). The R2 value of 12.19% suggests a modest influence on the part of instructional methods.

Table 8
Mean Scores and Standard Deviations by Learning Method for Awareness and Education Variability

Method	Pretest	Post-test				
Test	Method	Mean	Std. Deviation	Min	Max	N
Pretest	ChatGPT	.00	.000	0	0	15
	HR	.44	.892	0	3	16
	Google	.57	.646	0	2	14
	Books	.09	.302	0	1	11
	Peer Discussion	.33	.651	0	2	12
	Frontal Teaching	.13	.352	0	1	15
	Control Group	.50	.905	0	3	12
Post-test	ChatGPT	1.93	.704	1	3	15
	HR	.69	.946	0	3	16
	Google	1.14	1.231	0	3	14
	Books	.18	.603	0	2	11
	Peer Discussion	1.42	.900	0	3	12
	Frontal Teaching	.93	1.163	0	3	15
	Control Group	.50	.905	0	3	12

Table 8 shows relatively uniform learning outcomes, with no method clearly outperforming the others, indicating that awareness and education may be enhanced through diverse teaching strategies, provided they actively engage learners.

Energy Efficiency and Renewable Sources

Analysis revealed a statistically significant intercept ($F(1, 88) = 64.046$, $p < .001$) and notable method differences ($F(6, 88) = 4.172$, $p < .001$; R2 = 22.15%), indicating that the instructional approach influenced learning outcomes in this category.

Table 9
Mean Scores and Standard Deviations by Learning Method for Energy Efficiency and Renewable Sources Variability

Method	Pretest	Post-test				
Test	Method	Mean	Std. Deviation	Min	Max	N
Pretest	ChatGPT	.00	.000	0	0	15
	HR	.25	.447	0	1	16
	Google	.21	.426	0	1	14
	Books	.09	.302	0	1	11
	Peer Discussion	.17	.389	0	1	12
	Frontal Teaching	.07	.258	0	1	15
	Control Group	.00	.000	0	0	12
Post-test	ChatGPT	.60	.507	0	1	15
	HR	.87	.619	0	2	16
	Google	.79	.975	0	3	14
	Books	.09	.302	0	1	11
	Peer Discussion	.42	.515	0	1	12

	Frontal Teaching	.06	.507	0	1	15
	Control Group	.00	.000	0	0	12

Post-hoc Tukey HSD tests revealed significant gains between HR and Books (MD = -.47, SE = .140, p = .019, 95% CI [-0.90, -0.05]), HR and the control group (MD = -.56, SE = .137, p = .002, 95% [-.98, -.15]), and Google and the control group (MD = -.50, SE = .141, p = .011, 95% CI [-.93, -.07]). These results (Table 9) indicate that HR and Google were more effective in promoting energy efficiency awareness compared to Books and the control group. While these differences are statistically significant, causal interpretation should be approached with caution due to potential contextual influences.

Sustainable Waste Management

ANOVA showed a significant intercept ($F(1, 88) = 51.959$, $p < .001$), but no statistically significant differences between methods ($F(6, 88) = 0.654$, $p = .686$), with an R2 of 4.27%, indicating minimal influence on the part of instructional approach.

As shown in Table 10, mean scores were consistent across all methods, suggesting that no particular approach demonstrated a clear advantage in enhancing waste management competences.

Table 10

Mean Scores and Standard Deviations by Learning Method for Sustainable Waste Management Variability

Method	Pretest		Post-test			
Test	Method	Mean	Std. Deviation	Min	Max	N
Pretest	ChatGPT	.27	.458	0	1	15
	HR	.50	.632	0	2	16
	Google	.50	.650	0	2	14
	Books	.18	.405	0	1	11
	Peer Discussion	.33	.492	0	1	12
	Frontal Teaching	.33	.488	0	1	15
	Control Group	.33	.492	0	1	12
Post-test	ChatGPT	.40	.507	0	1	15
	HR	.50	.632	0	2	16
	Google	.79	.893	0	2	14
	Books	.36	.809	0	2	11
	Peer Discussion	.50	.522	0	1	12
	Frontal Teaching	.53	.516	0	1	15
	Control Group	.33	.492	0	1	12

The Role of New Literacies in Empowering Youth

This section explores how new literacies equip youth with the skills needed for a sustainable future through advanced technologies. The study highlights the importance of competences in both digital and analogue learning environments, aligned with the DigComp 2.2 framework, which outlines 21 key competences. Table 11 compares how different learning methods contribute to these competences, distinguishing between comprehensive digital skill development and foundational knowledge acquisition.

Table 11
Knowledge, Skills and Attitudes by Learning Method

Method of Learning	Identified Competences	Competency Depth
ChatGPT	1–21	Comprehensive
HR	1–21	Comprehensive
Google	1–21	Comprehensive
Books	1–21	Fundamental
Peer Discussion	1–21	Fundamental
Frontal Teaching	1–21	Fundamental
Control Group	None	Non-applicable

*Specific knowledge, skills and attitudes according to key components of digital competence are numbered and thus explained in Table 2.

Contemporary methods (e.g. ChatGPT, HR, and Google) support broad engagement across all 21 competences, enhancing not only digital literacy but also critical thinking, creativity, and collaboration, making them valuable tools in sustainability education. Traditional methods, such as books, peer discussion, and frontal teaching, focus on foundational competences. While they do not provide the same depth as digital methods, they establish essential groundwork that supports the later integration and development of advanced digital skills.

Together, these findings underscore the complementary roles of digital and traditional approaches. Digital methods drive comprehensive literacy development, whereas traditional methods ensure a strong foundational base, preparing students to engage effectively with advanced technologies in meaningful ways.

Discussion

The study contributes to existing literature by examining how advanced technologies, such as generative language models and HRs, support sustainability and EE. The findings suggest that these technologies can be as effective as, and sometimes more effective than, traditional methods (RQ1), in line with Burbles et al. (2020) and Mian et al. (2020), which emphasize the transformative potential of digital tools in education. HRs demonstrated significant improvement in response variability (RQ2), complementing studies on the role of digital technologies in fostering engagement with sustainability goals (Portuguez Castro and Gomez Zeremeno, 2020; Schina et al., 2020).

The integration of advanced technologies appears to enhance environmental awareness and digital competences, fulfilling the DigComp framework's competences (RQ3). While digital methods promote comprehensive, multi-domain competency development, traditional approaches provide essential foundational skills, highlighting the synergistic relationship between these two educational strategies.

Young future teachers play a crucial role in promoting sustainability, as their perspectives shape long-term educational strategies. Equipping them with expertise in advanced technologies is essential for fostering sustainable education.

Limitations of the study include its focus on a geographically and culturally limited sample of Slovenian future teachers, which may reduce generalizability.

The quasi-experimental design limits causal inferences, and the study examines only short-term impacts, leaving long-term effects unexplored. Future research should focus on the sustained impact of contemporary technologies on sustainability education and young educators' ability to lead sustainable initiatives. Broadening the sample diversity could also enhance representativeness.

In the context of global sustainability efforts, this research highlights the strategic importance of educational technologies in empowering young people to address environmental challenges. The digital age offers innovative, interactive opportunities for active and critical learning that go beyond traditional methods, making technological integration a key enabler for achieving sustainable development goals.

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