Currículo
Programa de Pós-Graduação em Educação
PUC-SP 50 anos
REVISTA DO PROGRAMA DE PÓS-GRADUAÇÃO EM EDUCAÇÃO: CURRÍCULO
DOI http://dx.doi.org/10.23925/1809-3876.2025v23e73918

Playing the Whole Game: How Open Schooling with STEM and AI Empowers Students to Transform Lives and the Planet

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Abstract

This article argues that Artificial Intelligence (AI) literacy and transversal skills do not emerge from fragmented and decontextualised approaches, nor from technology access alone. Instead, they develop through open schooling when students engage with meaningful community problems they care about, build relevant curriculum knowledge, and act with schools, families, and scientists. Across three countries, six teachers implemented CARE-KNOW-DO with 330 students from low-income families aged 12–19. This qualitative study analyses teachers' lesson reports, surveys, and interviews, triangulating student findings to identify convergence without re-analysis. Country contrasts reveal contextual variations and pedagogical inflections, offering rigorous interpretation without implying causality. Linking Freire's pedagogy of autonomy, Perkins' playing-the-whole-game, and Hodson's action-oriented education with CARE-KNOW-DO, pedagogical design was identified as the primary lever for equity in confidence, agency, and aspiration, with teachers positioned as key educators in empowering students now and in the future.

Keywords: open schooling; CARE-KNOW-DO; pedagogical design; student eco-outwards agency; transversal skills.

Jogando o jogo inteiro: como a escolarização aberta com STEM e IA empodera os estudantes para transformar vidas e o planeta

Resumo

Este artigo argumenta que o letramento em Inteligência Artificial (IA) e as competências transversais não emergem de abordagens fragmentadas e descontextualizadas, nem do mero acesso à tecnologia. Em vez disso, desenvolvem-se por meio da escolarização aberta, quando os estudantes se envolvem com problemas comunitários significativos que lhes interessam, constroem conhecimento curricular relevante e atuam em colaboração com escolas, famílias e cientistas. Em três países, seis professores implementaram o CUIDAR-SABER-FAZER com 330 estudantes de famílias de baixa renda, com idades entre 12 e 19 anos. Este estudo qualitativo analisa relatórios de aulas, pesquisas e entrevistas, triangulando os resultados dos estudantes para identificar convergência sem reanálise. Os contrastes entre países revelam variações contextuais e inflexões pedagógicas, oferecendo uma interpretação rigorosa sem implicar causalidade. Ao articular a pedagogia da autonomia de Freire, o "jogo inteiro" de Perkins e a educação orientada para a ação de Hodson com o CUIDAR-SABER-FAZER, o design pedagógico foi identificado como a principal alavanca para a equidade em confiança, agência e aspiração, com os professores posicionados como educadores-chave para capacitar os estudantes no presente e no futuro.

***Palavras-chave**: escolarização aberta; CARE-KNOW-DO; design pedagógico; agência estudantil eco-externalizada; competências transversais.*

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DOI http://dx.doi.org/10.23925/1809-3876.2025v23e73918

Jugando el juego completo: cómo la escolarización abierta con STEM e IA empodera a los estudiantes para transformar vidas y el planeta

Resumen

Este artículo sostiene que la alfabetización en Inteligencia Artificial (IA) y las competencias transversales no surgen de enfoques fragmentados y descontextualizados, ni del mero acceso a la tecnología. Por el contrario, se desarrollan a través de la escolarización abierta, cuando el estudiantado se involucra en problemas comunitarios significativos que le importan, construye conocimiento curricular relevante y actúa en colaboración con escuelas, familias y científicos. En tres países, seis docentes implementaron el modelo CUIDAR–SABER–HACER con 330 estudiantes de familias de bajos ingresos, con edades entre 12 y 19 años. Este estudio cualitativo analiza informes de aula, encuestas y entrevistas, triangulando los resultados del estudiantado para identificar convergencia sin reanálisis. Los contrastes entre países revelan variaciones contextuales e inflexiones pedagógicas, ofreciendo una interpretación rigurosa sin implicar causalidad. Al articular la pedagogía de la autonomía de Freire, el enfoque del "juego completo" de Perkins y la educación orientada a la acción de Hodson mediante el modelo CUIDAR–SABER–HACER, el diseño pedagógico se identifica como la principal palanca para la equidad en confianza, agencia y aspiración, con el profesorado posicionado como educadores clave para capacitar al estudiantado en el presente y en el futuro.

***Palabras clave**: escolarización abierta; CUIDAR–SABER–HACER; diseño pedagógico; agencia estudiantil; competencias transversales.*

1 INTRODUCTION

In an era of accelerating climate crisis, widening digital divides, and urgent sustainability challenges, education must become a force for transformation, not simply for knowledge transmission. In 2015, four historic milestones reshaped the global educational landscape: (1) the adoption of the Sustainable Development Goals (UNGA, 2015); (2) the Paris Agreement on Climate Change (UNFCCC, 2015); (3) the founding of OpenAI, guided by principles oriented toward the common good of humanity (OpenAI, 2015); and (4) the launch of open schooling by the European Commission as a novel approach to empowering students to address real-world challenges in collaboration with families, researchers, and society (EU, 2015). A decade later, in 2025, the reality is sobering. SDG targets remain far from Agenda 2030 achievement, the Paris Agreement faces intensifying climate catastrophe, and OpenAI generates serious concerns about social inequalities and digital divides. Despite large-scale investments and international partnerships, open schooling remains poorly understood, ambiguous, and fragmented into isolated projects, rarely embedded in institutional practice. There is a lack of a robust reference framework for

DOI http://dx.doi.org/10.23925/1809-3876.2025v23e73918

sustainability-oriented open schooling with AI; this study addresses this gap across three countries (Okada, 2024, 2025).

However, this moment also represents a turning point. In the context of open schooling, the CONNECT project, supported by the European Commission, focuses on communities facing socioeconomic challenges—from the Amazon to the Mediterranean, from under-resourced neighborhoods in the UK to rural Greece. Evidence from studies conducted within this project shows that when teachers adopt the CARE-KNOW-DO pedagogy, grounded in real-world issues that matter to students, integrating the required curricular knowledge and actions with local experts and families, transformative learning occurs. Students who were previously disengaged become investigators, teachers shift from knowledge transmitters to collaborative facilitators, and families move from passive supporters to co-educators and partners in their children's learning (Okada, 2023, 2024, 2025).

Based on this evidence, this article proposes an integrated system of open schooling with AI and climate action, and examines how teachers, acting as educator-researchers, empower students in contexts of socioeconomic inequality to develop as agents of change.

2 THEORETICAL FOUNDATION

Educational transformation remains fragile, constrained by interconnected barriers across students, teachers, and education systems (Ainscow & Chapman, 2025). Curricula centered on fragmented content and high-stakes assessments tend to foster student disengagement; teachers face structural constraints that inhibit authentic inquiry and collaborative pedagogy; and education systems prioritize content coverage and assessment over competencies such as adaptability, ethical reasoning, and social problem-solving. Emerging technologies, such as Artificial Intelligence (AI), can either intensify these inequalities or open new opportunities, depending on the pedagogical design adopted (OECD, 2024; TechUK, 2025).

Open Schooling challenges transmissive education by centering the problematization of real-world issues through partnerships within and beyond the school. It enables practices in which AI acts as a tool for equitable, problem-oriented learning, connecting schools, families, communities, and scientists, preparing students to responsibly address complex global challenges (EU, 2015).

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Unlike "open school," which emphasizes flexible curricula, and "open education," focused on content access, open schooling centres learning on real social challenges and transformative collective action co-led by students (Okada, 2023). The CARE–KNOW–DO model (Okada & Sherborne, 2018; Okada & Gray, 2023; Okada, 2025) operationalizes these foundations as an integrated pedagogical system for the 2030 Agenda, in which caring is constituted through knowing in action. CARE, KNOW, and DO are not linear stages but interdependent dimensions in which emotion, ethics, knowledge, and action are co-constructed in socially situated contexts.

This integration rests on three theoretical perspectives. Freire (1970) critiques the banking model: "*the more students work to store the deposits entrusted to them, the less they develop critical consciousness*" (p. 54). For him, education is never neutral: it functions either as an instrument of domestication or as a practice of freedom. His pedagogy of problematization engages learners as co-investigators of real situations, promoting critical consciousness, ethical reasoning, and collective agency through praxis, understood as the inseparable unity of reflection and transformative action (Freire, 1998).

Convergently, Perkins (1992, 2009) identifies structural problems of traditional education: *elementitis*, the fragmentation of knowledge into isolated “elements”, and *aboutitis,* excessive learning "about" topics without deep understanding or practical capacity. As he summarizes: "*Elements first. Gradually increase to complexity by learning the elements now and putting them together later. Learning about. Learn something from the beginning, rather than learning to do*" (Perkins, 2009, p. 4).

These forms of fragmentation hinder knowledge construction and the transfer of skills. To overcome them, Perkins (2009) proposes ‘whole game learning,’ in which students engage from the outset in authentic, albeit simplified, practices that integrate knowledge, skills, and metacognition.

Hodson (2014, p. 1) argues that "traditional science education is timid in its approach to the political interests and social values that underpin scientific and technological developments". His four-dimensional model—learning science, learning about science, doing science, and engaging in sociopolitical action—connects scientific knowledge to socioscientific issues of social, environmental, economic, and ethical relevance, to form and inform citizens capable of acting responsibly on issues involving science and technology.

DOI http://dx.doi.org/10.23925/1809-3876.2025v23e73918

The previous study, complementary to the present investigation, on open schooling showed that pedagogical integration fostered the development of seven transversal student competencies: proactive exploration, affective engagement, STEM for sustainability, problem-solving, future-oriented thinking, scientific citizenship, and authentic learning (Okada, 2025). These competencies align with the *Open Schooling Declaration* (2024) and UNESCO's *AI Competency Framework*, integrating the levels of understand–apply–create through socially situated practices (Okada et al. 2025). AI literacy, operationalized through the dimensions CARE–UNDERSTAND (ethical–critical awareness), KNOW–APPLY (critical and contextualized use), and DO–CREATE (responsible innovation with social impact), emerged from integrated and action-oriented formative processes.

Advancing the literature, the present study shifts the focus from student outcomes to the teacher mechanisms and teaching experiences that sustain these learning processes. Its aim is to examine how curricular design and the transformation of teachers into educator-researchers catalyze students' eco-externalized agency. The study is grounded in the integrated CARE–KNOW–DO model, theoretically anchored in critical consciousness (Freire, 1998), authentic and holistic learning (Perkins, 2009), and future-oriented, responsible community action (Hodson, 2014). The guiding research question is: How do teachers orchestrate pedagogical mechanisms (CARE–KNOW–DO) to educate an eco-outwards generation for the AI era, and what achievements, motivating factors, barriers, and turning points emerge from this process in contexts of inequality?

3 METHODOLOGY

This study constitutes an in-depth transnational qualitative investigation, grounded in intercultural participatory action research (McTaggart, 2000) to investigate the implementation of AI-integrated open schooling activities within the CONNECT project, a Horizon 2020 initiative of the European Union under the "Science with and for Society" scheme. Unlike previous studies centred on transversal competencies of 1,500 teachers and 50,000 students across the CONNECT network, this study at a considerably smaller scale focused on in-depth investigation of the roles, practices, and challenges of six secondary teachers (Brazil, Greece, and United Kingdom) and their 330 students, drawn from public schools and low-income families.

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The study engaged 6 secondary school teachers (1 female from Brazil, 3 males and 1 female from Greece, and 1 male from the United Kingdom) and their 330 students aged 12-19 from state schools and low-income families who completed three AI-integrated Open Educational Resources (OERs) aligned with Sustainable Development Goals. Student demographics included 158 female, 158 male, and 14 other gender identities, distributed across three age groups: young (12-13), medium (14-15), and older (16-19). Greece contributed the largest cohort with 155 students taught by four teachers (46 young, 59 medium, 50 older); Brazil contributed 125 students taught by one teacher (26 young, 40 medium, 59 older); and the UK contributed 50 students taught by one teacher (10 young, 13 medium, 27 older). Only 56 participants had parents in science-related fields, and while 224 had mobile phones with internet, many lacked personal computers at home, reflecting the socioeconomically disadvantaged contexts targeted by CONNECT.

Teachers voluntarily participated in the CONNECT project following three professional development workshops focused on: (1) understanding the CARE-KNOW-DO pedagogical framework, participatory research principles, and data co-production methods; (2) co-developing open schooling activities integrating families, scientists, and AI tools with coach guidance; and (3) coaching interaction protocols, reporting practices, and sharing implementation experiences, including pedagogical challenges and student learning evidence.

The intervention consisted of implementing three AI-integrated OERs (Box 1) addressing real-world sustainability challenges through the CARE-KNOW-DO framework mapped to UNESCO's AI Competency levels (UNDERSTAND-APPLY-CREATE) using OER:

Box 1 - Open Educational Resources (OERs) with AI activities for the 2030 Agenda

OER SDG	Title	AI Tools	Teamwork Methods
SDG15 (Grécia)	AI-Powered Wildfire Detection	Machine learning and image recognition using Scratch for drone photo classification.	Co-creation with scientists; Evaluation by a jury supported by families.
SDG13, SDG14 (Brasil)	AI-Powered Investigation Mapping for Drought	AI-Supported Query Mapping Tools (Whimsical).	Conversation circles involving members of the school and the community; Peer-to-peer mentoring with scientists.

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OER SDG	Title	AI Tools	Teamwork Methods
SDG 7 (Reino Unido)	AI Fundraising Campaign for Sustainable Energy	Canva AI, ChatGPT and app.diagrams.net.	Small group discussions, full-class debates with scientists; consensus building through voting with families.

Source: Author's elaboration.

Each OER followed a structured seven-step implementation process: (1) school heads received information from CONNECT coaches and joined platform webinars with STEM teachers; (2) teachers met coaches to discuss the CARE-KNOW-DO model and developed lesson plans integrating AI; (3) students discussed real-life challenges and AI activities; (4) scientists presented authentic problems; (5) students selected approaches and interpreted problems with teachers; (6) students planned solutions, discussed with families to activate prior knowledge, and engaged in guided problem-solving; and (7) students completed self-reflective instruments documenting outputs and outcomes.

This participatory action research with qualitative design (Box 2) generated multiple data sources to capture teachers' implementation experiences and coaching effectiveness:

Box 2 - Qualitative Datasets

Teacher ethnographic accounts: Detailed narratives documenting implementation strategies, lesson adaptations, student progress, coaching interactions, encountered barriers, and pedagogical decision-making throughout the OER activities. **STEM researcher observations:** Systematic field notes capturing classroom dynamics, teacher-student-scientist interactions, AI tool integration processes, family engagement patterns, and knowledge co-construction trajectories. **Post-implementation surveys and reports**: Structured questionnaires and reflective reports completed by teachers detailing outcomes, challenges, required coaching support, student achievements, and recommendations for future practice. **Post-implementation interviews**: Semi-structured interviews exploring institutional perspectives on project value, systemic barriers, sustainability prospects, and policy implications.

Source: Author's elaboration.

All research materials underwent translation following International Test Commission standards to ensure linguistic and cultural equivalence across English, Greek, and Portuguese contexts. Data analysis employed the CARE-KNOW-DO coaching assessment framework adapted from the student skills instrument. Teacher practices were analysed across three pedagogical dimensions:

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- **CARE Phase (ethical engagement**): Community partnership facilitation, student voice and choice enablement, emotional and ethical engagement strategies, critical consciousness development about AI fairness and justice, and diverse perspective integration.
- **KNOW Phase (epistemic practices**): Authentic challenge design with community/expert partnerships, technical skill scaffolding connected to larger purpose, conceptual understanding development strategies, epistemic practices (inquiry, evidence reasoning, argumentation) facilitation, and progression from guided to independent competency.
- **DO Phase (transformative action):** Student action support resulting in real outputs with real consequences, community/organizational engagement documentation, scientific citizenship facilitation through dialogue and deliberation, student agency and influence enablement, and iterative improvement based on external feedback.

The interpretation of teacher quotes was contextualised by comparing variations across countries and triangulating them with student artefacts and reflective reports. Thematic analysis followed Braun and Clarke (2006), integrating thick description (Geertz, 1973) and theoretical triangulation drawing on notion of understanding in context (Perkins, 2009), emphasis on critical awareness and praxis (Freire, 1970), and focus on social action (Hodson, 2014).

The research received ethical approval in Greece, Brazil, and the United Kingdom, with informed consent obtained from all participants in accordance with Horizon 2020 standards. To mitigate interpretive bias, three safeguards were adopted: the generation of reflective primary data by teachers, international triangulation, and external peer review. Negative cases were systematically analysed to identify contextual variation or implementation conditions rather than limitations of the framework. Triangulation cross-referenced reports, observations, artefacts, and reflections across the three countries, ensuring analytical consistency and construct validity. All materials were securely stored in the ORDO repository.

4 FINDINGS

Regarding the implementation of CARE–KNOW–DO, seven mechanisms show how teachers put the sequence into practice. The model was used in an integrated

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manner, consolidating itself as a reference framework for the emancipatory use of AI in open schooling. In this choreography, teachers activated intrinsic care through democratic choice, legitimised inquiry with experts, and channelled learning into community actions with real consequences.

Concerning the achievements reported by teachers, students developed complex skills, such as machine-learning workflows for forest protection, energy reasoning applied to solar solutions, and participation in structured protocols for discussing water scarcity. The pedagogical design, grounded in real-world issues, functioned as an in-service continuing professional development pathway, strengthening both teacher and student motivations, such as engagement, agency, and resilience. At the same time, teachers faced persistent barriers, including lack of time, prerequisite demands, inclusion challenges, and a lack of systemic recognition. The turning points show how teachers overcame the *aboutitis* and *elementitis* described by Perkins (2009), and how they reinforced Freirean dialogue and Hodsonian activism, carefully orchestrated through the seven mechanisms that emerged as key results for conceptualising students' eco-externalised agency.

4.1 Democratic student choice with socioscientific argumentation

Teachers cultivated authentic care by offering students genuine choice, situating socioscientific learning, and linking schoolwork to consequences that extend beyond grades. Democratic mechanisms of student choice translated abstract argumentation into concrete and assessable classroom practice across all three national contexts. The exercise of student choice aligns with the central critique of Perkins (2009), countering *aboutitis* by transforming teaching into authentic decision-making practices that connect assessable knowledge to real-world situations.

When students exercised genuine agency over research questions, discussion topics, or investigative foci, teachers reported observable shifts in student engagement and in their own pedagogical confidence. Rather than practising argumentation as a decontextualised skill, students engaged in evidence-based reasoning because it served their own purposes—such as deciding which invention to fundraise for, determining which community questions to pose to scientists, or prioritising drought mitigation strategies. This exemplifies what Perkins (2009) terms learning by wholes

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(playing the whole game): students experience, from the outset, the authentic and integrated activity of scientific citizenship, even at early levels.

Critically, democratic choice also functioned as what Freire (1970) termed *problem-posing education*, in contrast to *banking education*. Students were not passive recipients of teacher-defined problems, but co-investigators who named and framed the challenges they would address. This shift positioned learners as subjects capable of reading and rewriting their worlds, rather than as objects acted upon by predetermined curricula. The resulting argumentation was not performative compliance, but genuine praxis—reflection and action in service of community transformation. Teachers reported that this made student thinking visible and assessable in ways that scripted debate exercises never achieved, because students owned the stakes of the inquiry. Across contexts, democratic choice acted as a mechanism that converted argumentation from teacher-directed activity into student-owned practice.

The pattern evident in the following extracts (Box 3) suggests that when students control the parameters of inquiry, they engage more authentically in evidence-based reasoning, making their argumentation processes visible and assessable to teachers.

Box 3 - Democratic student choice with socioscientific argumentation

Data from interview	Notes in lesson plan and reports
“Students debated and selected the 'solar cap' over a 'river charger,' turning evidence-based choice into the learning itself through collective reasoning.” British teacher	Structured debate required explicit weighing of evidence and trade-offs. This provided authentic artifacts for assessing claims and strengthened teacher confidence in argumentation assessment.
“The students initially managed to form groups without the involvement of the teacher [...] chose by vote the ones they would discuss with their parents.” Greek teacher	Student self-organization reduced facilitator burden while maintaining inquiry quality. They also reported smoother facilitation of question generation because learners’ questions guided their inquiry.
“Students expressed an emotional connection to the drought situation in the Amazon [...]” Brazilian teacher	Affective issues placed transformed discussion quality. Ownership increased, and the teacher could anchor evidence-based talk in community urgency.

Source: Author’s elaboration.

The theoretical significance extends beyond engagement. Hodson (2014) argues that science education must prepare students for civic activism on socioscientific issues—climate change, resource management, public health—that

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demand not just conceptual understanding but the capacity to deliberate, decide, and act collectively. Democratic choice mechanisms created the conditions for this: students practiced the epistemic and social dimensions of scientific citizenship simultaneously, learning both how to evaluate evidence and how to negotiate divergent perspectives toward shared action. This is Perkins's "whole game" in Hodson's activist register and Freire's praxis: students played the complete role of citizen-scientist from the outset, making consequential choices with real community implications.

4.2 Encounters with experts in real-world contexts

Just-in-time expert encounters legitimize student inquiry, make abstract concepts manipulable, and resolve teacher uncertainty about facilitation. Direct contact with domain experts represented a critical inflection point in teacher confidence and student understanding across all implementations. Teachers consistently described this as a "before and after" moment that clarified abstract concepts and legitimized classroom activities. This finding illuminates also the practical mechanism for addressing what Perkins (2009) calls the *aboutitis* problem—learning *about* subjects without engaging in authentic practice. Prior to expert contact, students were studying *about* machine learning, forest ecology, or renewable energy as abstract disciplinary content. The expert encounter transformed this into learning-by-doing-the-discipline: students were now engaged in the same epistemic practices—hypothesis generation, model training, data curation, peer review—that scientists actually use, validated by the scientists themselves.

The mechanism appears to operate through two pathways: first, legitimizing the classroom activity by connecting it to authentic scientific practice, which addresses students' persistent question "why does this matter?"; second, providing concrete referents that make abstract concepts manipulable, addressing the cognitive challenge of reasoning about invisible processes (e.g., how neural networks classify images, how solar cells convert photons to electrons). These pathways are mutually reinforcing. When a materials scientist demonstrates plastic recycling in a university laboratory, students gain both conceptual clarity (they see polymerization processes) and motivational purpose (they understand their classroom model serves the same function as the scientist's research).

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Expert contact functioned as a critical turning point that resolved ambiguity about both content and pedagogy. The mechanism appears to operate through two pathways: legitimizing the classroom activity by connecting it to authentic scientific practice and providing concrete referents that make abstract concepts manipulable. These can be observed in the following extracts (Box 4):

Box 4 - Encounters with experts in real-world contexts

Data from interview	Notes in lesson plan and reports
"Initially, it was not clear [...] This began to change after meeting the scientist and when they began to train their AI models on their own." Greek teacher	Greek teachers described a dramatic shift in their own understanding and confidence following expert engagement. This inflection helped Scratch integration, areas previously linked to lower initial confidence.
"A visit to the Department of Materials Science and Technology. Labs [...] who prepared plastic for them." Greek teacher	Multisensory expert experiences deepened understanding in lasting ways. These encounters translated abstract concepts into manipulable experiences and clarified next steps in the classroom.
"We need to scaffold knowledge construction during expert encounters." British teacher	In the UK, external experts served as the inspirational masters who legitimized the work.

Source: Author's elaboration.

From a Freirean perspective, expert encounters embodied dialogical pedagogy. Scientists did not "deposit" knowledge into passive students but engaged in horizontal dialogue where students posed authentic questions emerging from their community investigations. This dialogue transformed the traditional teacher-student hierarchy: teachers became co-learners alongside students, and students experienced themselves as legitimate knowledge-seekers whose questions warranted expert attention. This shift is crucial for developing critical consciousness—students began to see knowledge not as a fixed body of truths owned by authorities but as a dynamic, constructed, and contestable process in which they could participate.

Hodson (2014) emphasises that an activism-oriented science education requires students to understand both the substantive content of scientific disciplines and the sociopolitical contexts in which science operates, articulated in four learning goals: learning science (concepts), learning about science (the nature of scientific knowledge), doing science (inquiry practices), and addressing socioscientific issues (civic engagement). In the encounters with specialists, the scientists explained not only technical content but also the institutional constraints, ethical dilemmas, and defensive

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strategies they face, modelling for students what it means to be a scientist-citizen in the face of real-world challenges and thus simultaneously integrating these four goals. Consistent with this view, Hodson (2014) also argues that science education aimed at social change requires outward-looking schools that establish partnerships with communities rather than functioning as insular and closed credentialling systems. Building on this perspective, this study conceptualises "eco-outwards" (as a synonym for eco-externalised) to describe an education that opens itself to a real, sustainable world perspective centred on people and planet.

4.3 Digital collaboration with families that integrates local knowledge

Collaborative platforms allow families to become intellectual partners, rather than merely homework assistants, extending the learning community beyond the school walls. Digital tools enabling family co-authorship shifted families from peripheral observers to active interlocutors in students' work. This transformation supported students' effort between classes and increased teachers' confidence in guiding complex inquiry processes. Simple collaborative tools—particularly *Google Docs* for shared writing, concept mapping platforms for visualizing student thinking, and asynchronous discussion forums—transformed family participation from compliance-based homework checking to substantive intellectual co-authoring. This directly addresses the concern about the artificiality of school learning: when families co-author student inquiry, the boundary between "school knowledge" and "community knowledge" dissolves. Learning is no longer confined to the classroom but becomes a continuous, distributed process embedded in family conversation and community problem-solving (Perkins, 2009).

The mechanism appears to work by making students' thinking visible to families in real time and by creating low-barrier entry points for family contribution. When students' drought mapping appears in a shared document or is discussed at home, parents and siblings can add local knowledge, ask clarifying questions, or connect the investigation to family livelihood concerns, without requiring formal scientific training. This democratizes participation in ways that traditional homework (e.g., "ask your parents to check your assignment") does not, such as exploring ways to access potable water during drought periods. Families should be valued and engaged in education for what they truly are—bearers of cultural knowledge, life experiences, and community

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belonging—not treated as "substitute teachers" responsible for correcting, monitoring, or reinforcing school content at home. Simple collaborative tools transformed family participation from compliance-based homework checking to substantive intellectual co-authoring. The mechanism appears to work by making student thinking visible to families in real-time and creating low-barrier entry points for family contribution. These can be detected as follows (Box 5):

Box 5 - Digital collaboration with families that integrates local knowledge

Data from interview	Notes in lesson plan and reports
"A good practice is the use of collaborative *Google Docs* [...] Very good, since 95/100 participated in the work." Greek teacher	High participation rates and qualitative shifts in family roles occur through collective docs. It helps student effort between lessons and guiding reliable sourcing.
"The students were given a sheet with topics to discuss at home [...] There was moderate participation, mainly due to lack of time for parents." Greek teacher	Family dialogue generated better questions even under time constraints. Even where time constrained some homes, teachers could still harness parent-student conversations to refine inquiry focus.
"Students co-create a research agenda and launch a campaign for action [...]" Brazilian teacher	The resulting maps were discussed with the community, leading to a list of actions decided by the members.
"We need to orchestrate knowledge construction by aligning family dialogue with classroom inquiry." British teacher	Homework discussions with families helped students choose the invention. Families acted as participants in the inquiry process, rather than as content couriers or as checkers of their children's homework

Source: Author's elaboration.

From a Freirean (1970) lens, family co-authoring exemplifies "reading the world and the word" simultaneously. Students and families together name their reality—drought impacts, energy poverty, forest degradation—and jointly construct knowledge to transform it. This is praxis in its fullest sense: reflection (dialogue about the problem) and action (co-designing solutions) are inseparable and mutually constitutive. Families are not auxiliary support staff but co-investigators with essential expertise. This challenges the deficit narratives often applied to low-income, immigrant, or Indigenous families: far from lacking capacity to support learning, these families possess deep knowledge about local ecosystems, economic systems, and social dynamics that formal schooling systematically excludes.

Hodson (2014) argues that science education aimed at social change requires schools to become "outward-looking" institutions, partnering with communities rather than functioning as insular credentialing systems. The term *eco-externalized*, as a

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translation of "eco-outwards," is conceived as opening up to a real-world perspective. Family co-authorship operationalizes this approach: schools position families as intellectual partners whose knowledge co-constructs the curriculum. This is particularly significant for underserved communities, where formal science education has historically invalidated or erased local knowledge systems. When Indigenous families in the Amazon contribute hydrological observations to students' drought maps, or when Greek immigrant families share fire management practices from their countries of origin, schools recognize these contributions as legitimate science—not folklore to be corrected, but experience to be integrated. This epistemic justice is central to Hodson's vision of science education in service of community empowerment, rather than disciplinary control.

4.4 Authentic activities that generate social value and competencies

When student work addresses real community needs or influences public discourse, motivation intensifies and competencies transfer across domains. Student work that produced real consequences on classroom assessment drove both motivation and skill development. When outputs addressed actual community needs or contributed to public discourse, students and teachers reported heightened purpose and observable skill transfer. Authentic outputs with public consequences created accountability structures that motivated sustained effort and facilitated skill transfer. This finding provides empirical support for the central pedagogical principle of Perkins (2009): students learn best when they "play the whole game" from the outset, engaging with authentic versions of disciplinary practice even at a junior level, rather than accumulating decontextualized skills in anticipation of eventual application. A fundraising campaign for solar caps deployed in off-grid communities, an AI drone simulation presented to forestry officials, drought maps discussed in community forums—these are not simplified proxies for real scientific citizenship but genuine instances of it, adapted to student developmental level.

The mechanism appears to operate through identity transformation: students position themselves as capable contributors to community problem-solving rather than as learners completing assignments. This shift from "student" identity to "citizen-scientist" identity has profound motivational consequences. When Greek students know forestry officials will review their AI classifiers, when Brazilian students see their

DOI http://dx.doi.org/10.23925/1809-3876.2025v23e73918

maps circulate in community meetings, when British students pitch to real investors, the quality bar rises organically—not because teachers demand it but because students recognize their work must be credible to external audiences. This internalized accountability drives far more rigorous self-editing, peer review, and iterative refinement than teacher-imposed rubrics can ever achieve.

Authentic outputs with public consequences created structures of authorship and accountability that motivated sustained effort and facilitated the transfer of skills. The mechanism appears to operate through identity transformation: students position themselves as capable contributors to community problem-solving, rather than merely as learners completing assignments. Some examples are presented as follows (Box 6):

Box 6 - Authentic activities that generate social value and competencies

Data from interview	Notes in lesson plan and reports
"Task 2: Design a fundraising page for an energy-saving device." British teacher	The UK teacher explained fundraising mechanisms. Students moved from calculating efficiencies to communicating value to real audiences, demonstrating transfer across mathematical, scientific, and rhetorical domains.
"[…] application in Scratch [...] drone [...] identify areas of illegal logging or illegal roads." Greek teacher	Greek teachers described deployable environmental tooling. Students built prototypes analogous to tools used by scientists, linking classroom models to field use and making abstract computational thinking concrete and purposeful.
"Students co-created a research agenda, actions were discussed with the community." Brazilian teacher	The Brazilian teacher documented participatory governance outcomes. Student research influenced community decision-making and public communication, positioning students as legitimate knowledge producers rather than knowledge consumers.

Source: Author's elaboration.

Freire (1970) insisted that authentic learning requires praxis—the dialectical unity of reflection and action. Authentic outputs embody this: students reflect critically on community challenges (Why are forests burning? How does energy poverty perpetuate inequality? What hydrological systems sustain Amazonian livelihoods?) and act transformatively to address them (building detection systems, launching campaigns, co-designing interventions). Critically, this action is not symbolic or performative; it has real consequences that students can observe, creating feedback loops that refine understanding. When community members respond to student proposals—accepting some recommendations, challenging others, requesting

DOI http://dx.doi.org/10.23925/1809-3876.2025v23e73918

clarifications—students experience the iterative, contestable nature of knowledge construction that Freire (1970, 1998) called "*conscientização"* (conscientisation). They develop not just technical competence but critical consciousness: the capacity to analyse power structures, recognize their own agency, and engage in collective action toward justice.

Hodson (2014) distinguishes between "science in the curriculum" (learning disciplinary content) and "curriculum for social activism" (using science to address community issues). Authentic outputs operationalize the latter. Students are not learning about renewable energy, machine learning, or hydrology as abstract disciplinary domains. They are *using* these tools to intervene in real problems—energy poverty, deforestation, drought. This positions STEM literacy not as cultural capital for individual advancement but as a tool for collective liberation, aligning with Hodson's argument that science education must prepare students to challenge injustice and imagine alternative futures. When Brazilian students co-design drought-response strategies with indigenous partners, they are not merely "applying" scientific knowledge; they are negotiating whose knowledge counts, what problems merit attention, and how solutions should be evaluated—the core epistemic and political work of scientific citizenship.

4.5 Explicit articulation of time constraints and prerequisites

Systemic constraints—time scarcity, rigid schedules, prerequisite sequencing gaps—limited implementation depth despite strong teacher motivation and successful local adaptations. These finding challenges dominant educational reform narratives that locate failure in insufficient teacher training or commitment. Instead, the data reveal that well-designed pedagogy (CARE-KNOW-DO) and highly motivated teachers repeatedly collided with institutional structures never designed to support whole-game, community-partnered, inquiry-based learning: rigid bell schedules fragmenting coherent investigation, assessment regimes valuing coverage over depth, prerequisite sequences assuming linear knowledge accumulation, and resource allocation prioritizing standardized inputs over adaptive support.

Time scarcity forced compromises in prerequisite instruction, while representation gaps in expert pools limited the intervention's equity impact despite teacher awareness. The pattern suggests that scaling requires policy-level

DOI http://dx.doi.org/10.23925/1809-3876.2025v23e73918

interventions in time allocation and expert recruitment rather than additional teacher professional development. Greek teachers explicitly named time as the limiting factor rather than lack of skill or commitment—they could orchestrate expert encounters, facilitate machine learning, and coordinate family co-authoring, but condensing these into conventional 45-minute periods required compromises that undermined pedagogical integrity. Teachers solved locally by chunking tasks and moving preparatory steps into homework but acknowledged these workarounds were unsustainable at scale and inequitable in effect (advantaging students with more family support or digital access at home). What this reveals is that the "whole game" cannot be played in fragments; authentic inquiry requires protected blocks of time for students to experience the natural rhythm of investigation—encountering problems, pursuing lines of thinking, hitting dead ends, regrouping, iterating—rather than artificial stopping points dictated by bells.

To illustrate these findings, some extracts are presented (Box 7):

Box 7 - Explicit articulation of time constraints and prerequisites

Data from interview	Notes in lesson plan and reports
"Time was limited." Greek teacher	They solved locally by chunking tasks and moving preparatory steps into homework.
"For example, I should have had time to teach more things in scratch before the script was implemented." Greek teacher	Greek teachers identified specific prerequisite gaps that time constraints prevented addressing.
"In the discussions, extroverted students dominated, and we had to change the technique." Brazilian teacher	Techniques were adapted with. asynchronous forum broadened participation and reduced dominance but required additional design time and platform familiarity.
"The scientist videos provided were all young white males! They asked for more inclusive examples! (this is quite a push at our school)." British teacher	The British teacher reported student awareness of representation gaps. Students named the problem, indicating both a design limitation and rising critical consciousness with equity implications.

Source: Author's elaboration.

From a Perkins (2009) perspective, structural time constraints reinforce precisely the fragmentation he critiques. Schools organize around discrete subject periods, isolated skills, and atomized assessments (*elementitis*) because this structure optimizes for content coverage and administrative efficiency, not for coherent learning. Playing the whole game requires reorganizing time: integrating disciplines (STEM with humanities with arts), extending investigation across multiple sessions, and aligning

DOI http://dx.doi.org/10.23925/1809-3876.2025v23e73918

assessment with authentic milestones (prototype demonstrations, community presentations) rather than arbitrary testing windows. Absent this reorganization, even the most skilled teachers can only approximate whole-game learning, diluting its transformative potential.

Freire (1970) would recognize these structural barriers as manifestations of the “banking” system he critiqued—educational structures designed not for liberation but for domestication, for producing compliant workers rather than critical citizens. Rigid schedules, standardized curricula, and high-stakes testing regimes all serve to make schooling predictable, controllable, and uniform—the antithesis of the emergent, contextual, dialogical pedagogy. The Brazilian teacher's need to adapt discussion protocols on the fly when extroverted students dominated is instructive: authentic dialogue requires flexibility to respond to emerging dynamics, but institutional structures rarely provide this flexibility. Teachers navigate these contradictions through localized resistance—"in the discussions, extroverted students dominated, and we had to change the technique”—but such resistance is exhausting and unsustainable without systemic change.

Hodson (2014) emphasizes that science education for activism requires not just curriculum reform but institutional transformation: schools must become sites of democratic participation, not bureaucratic compliance. The representation gaps identified by the British teacher—“The scientist videos provided were all young white males! They asked for more inclusive examples!”—illustrate this. Students' critical consciousness was developing (they noticed and challenged the lack of diversity), but institutional structures had not anticipated this. Expert recruitment protocols, video curation practices, partnership networks—all reflected default assumptions about who scientists are and which expertise counts. Addressing this requires deliberate institutional commitments to epistemic justice: cultivating diverse expert pools, compensating community knowledge-holders, and centring marginalized voices in knowledge co-construction. These are not technical fixes but political commitments requiring resources, accountability, and power redistribution.

4.6 Learning gains analysis by teachers

Conceptual understanding, technical skills, affective engagement, and collaborative capacity directly reflect the design mechanisms implemented by the

DOI http://dx.doi.org/10.23925/1809-3876.2025v23e73918

teachers. These outcomes demonstrated alignment with the proposed mechanisms, providing evidence that the project features functioned as theorized. Furthermore, consistency was observed with the mechanisms identified in findings one through five, indicating that the CARE–KNOW–DO design operated as intended.

This convergence between pedagogical design and observed outcomes is theoretically significant: it suggests that whole-game learning, when grounded in authentic problems and community partnership, produces both disciplinary competence and transversal skills development (UNESCO, 2014)—not as separate outcomes requiring distinct interventions but as integrated dimensions of the same learning process (Okada et al., 2024, 2025).

The UK teacher documented knowledge building connected to authentic outputs—students investigated energy efficiency and collaborated on fundraising materials. These products made argumentation and communication assessable, matching areas where teacher confidence improved through structured debate mechanisms. Knowledge outcomes included consolidation of scientific concepts: “They learnt that different solar cells had different efficiencies [...] consolidated their knowledge of energy transfer.” This illustrates the claim that deep conceptual understanding emerges when knowledge is constructed in service of meaningful goals, not through decontextualized instruction followed by delayed application (Perkins, 2009). Students did not first memorize energy-transfer formulas and then apply them; they encountered energy transfer as a tool needed to solve a problem they cared about (selecting an effective device to charge cell phones using solar energy by inventing the solar cap), developing both conceptual clarity and applied competence simultaneously.

Greek teachers documented skill acquisition in previously low-confidence domains following expert contact—machine learning model training, Scratch programming, reliable image sourcing. This directly addresses earlier teacher caution about guiding these technical processes. The mechanism is clear: expert legitimacy resolved teacher uncertainty, enabling facilitation of skills that had previously seemed opaque. Students “acquired skills in machine learning model training [...] acquired skills in scratch programming [...] gained skills in finding the right images online to train their models.” Critically, these technical skills were embedded within ecological understanding: students learned to classify deforestation patterns *while* learning how neural networks classify images, demonstrating the inseparability of disciplinary knowledge and computational thinking when learning is organized around authentic

DOI http://dx.doi.org/10.23925/1809-3876.2025v23e73918

problems rather than technical tutorials. The learning outcomes align with the mechanisms identified in the teachers' findings, providing evidence that the CARE–KNOW–DO design functioned as theorized, as follows (Box 8):

Box 8 – Learning gains analysis by teachers

Data from interview	Notes in lesson plan and reports
"Students watched videos of inventions [...] investigated the energy efficiency. They learnt that different solar cells had different efficiencies." British teacher	Knowledge building was connected to authentic outputs. These products made argumentation and communication assessable, matching areas where teacher confidence improved. Knowledge outcomes included consolidation of scientific concepts of energy transfer in the UK.
"Acquired skills in machine learning model training in scratch programming [...] They gained skills in finding the right images online to train their models." Greek teacher	Greek teachers documented skill acquisition in previously low-confidence domains following expert contact. This directly addresses earlier teacher caution about guiding reliable sourcing and facilitating machine learning and Scratch integration.
"THEY WERE MORE INTERESTED IN THE CLASSES." Brazilian teacher	In Brazil, teacher reported affective engagement shift connected to authentic civic outputs. Affective engagement connected to civic participation and public communication.

Source: Author's elaboration.

Greek teachers also documented how family co-authoring sustained participation and distributed cognitive load: "They learned about recycling the types of plastic [...] learned to use collaborative *Google Docs*." This reflects the insight that complex performances require distributed cognition—no individual possesses all necessary knowledge, so learning must be organized to leverage collective intelligence (Perkins, 2009). Family co-authoring operationalized this: students accessed family ecological knowledge, teachers provided scientific frameworks, experts offered technical guidance, and collaborative platforms made thinking visible across these groups. This is whole-game learning as collective accomplishment, not individual performance.

The Brazilian teacher reported a fundamental affective shift: "they were more interested in the classes". This intensified engagement directly reflects the authentic civic outputs mechanism—students cared because their work mattered beyond grades. From a Freirean (1970) perspective, this represents the emergence of critical consciousness: students recognized themselves as capable agents whose investigations carried real weight in community decision-making, transforming their

DOI http://dx.doi.org/10.23925/1809-3876.2025v23e73918

relationship to schooling from passive compliance to active co-construction of knowledge for liberation.

Hodson (2014) argues that science education oriented toward activism produces four interrelated outcomes: conceptual understanding (the "what"), epistemic understanding (the "how" of knowledge production), investigative competence (the "doing"), and civic engagement (the "why" and the "so what"). This perspective aligns with Freire (1970), who emphasizes emancipatory education in service of someone ("for whom") and in partnership ("with whom"), in which the ethical subject becomes capable of transforming their reality through a politicized reading of the world and action on real problems in collaboration with the planet.

The learning outcomes documented here demonstrate these aspects. Students developed conceptual knowledge (energy transfer, forest ecology, hydrological systems), epistemic knowledge (how scientists model phenomena, classify data, and evaluate evidence), investigative skills (training machine learning models, curating datasets, designing campaigns), and civic capacity (presentations to officials, co-design with communities, influencing public discourse) to benefit their communities alongside experts and their families. Critically, these competencies emerged in an integrated way—not as separate learning objectives—because the pedagogy was organized around the authentic, whole activity of scientific citizenship rather than fragmented into disciplinary silos. They played the entire CARE–KNOW–DO game.

4.7 Análise dos ganhos de aprendizagem pelos estudantes

The transformation experienced by the students aligns with an expanded ecological orientation: from school to the world and from the world to school, as theoretically conceived. Critical consciousness emerged when students moved from passive acceptance to active questioning of reality. Systems thinking developed as they realized that technological tools and collective action expand the possibilities for intervention. Community responsiveness grew as confidence in understanding enabled peer contribution and collaborative problem-solving. These three dimensions of the CARE-KNOW-DO model operated in an integrated manner, creating the eco-outwards agency essential for citizenship in sustainability, justice, and well-being in the AI era (Box 9).

DOI http://dx.doi.org/10.23925/1809-3876.2025v23e73918

Critical consciousness manifested when students questioned realities previously taken as immutable. The reflection of a Brazilian student illustrates this shift: “I learned that scientific research takes time and the importance of questioning our reality.” This movement represents Freirean conscientisation — transforming the understanding of the world through inquiry.

Box 9 - Análise dos ganhos de aprendizagem pelos estudantes

Thematic analysis	Student statements
Critical Consciousness: Ability to question reality; Examine power structures and assumptions	"I learned the importance of questioning our reality, being curious and developing solutions with people and AI" Brazilian girl, 16
Critical Consciousness: Ability to question reality; Examine power structures and assumptions	"I learned that some things could be done that I didn't think were possible, like creating an AI system for environmental protection" Greek girl, 14 years old
Systems Thinking: Ability to map relationships and visualize complexity	"AI is useful for mapping ideas and questions. It makes us think and helps us discuss solutions with scientists and our family beyond school." Brazilian boy, 14 years old
Community Response: Guidance for collective action; Willingness to work together	"I enjoyed working with friends and doing experiments to solve problems using AI, thinking on global challenges" boy from UK, 15
Community Response: Epistemic Trust: Readiness to Contribute Knowledge	"I'm confident about what I've learned from talking to others in the AI activities" UK girl, 16

Source: Author’s elaboration.

Systems thinking consolidated as students recognized previously unimaginable possibilities. The insight of a Greek student—“Some things could be done that I didn’t imagine possible, like creating AI systems”—exemplifies this epistemic shift. Peer statements about drought mapping showed how AI tools structured thinking: “AI was useful for mapping ideas and issues,” revealing an understanding of the technological mediation of complexity.

Community responsiveness combined confidence with collective action. A statement from a British student—“I feel confident about this topic with AI”—signals a solid epistemic foundation. This confidence enabled peer engagement: “I enjoyed working with friends and conducting experiments to solve problems.” Together, confidence and collaboration translate into readiness for eco-outwards action.

DOI http://dx.doi.org/10.23925/1809-3876.2025v23e73918

5 DISCUSSION

This study advances open schooling by proposing a transnational system of teacher education with AI and climate action, underpinned by the CARE–KNOW–DO model and the notion of eco-externalized agency. The findings reveal an articulated set of pedagogical mechanisms that make learning in AI and STEM an authentic socioscientific practice oriented towards socio-environmental justice and community participation in contexts of inequality (Carniel, Emmerson, & Gehrmann, 2024; OECD, 2019). Drawing on Perkins (2009), Freire (1970) and Hodson (2014), the argument is that the CARE–KNOW–DO model (Okada & Sherborne, 2018; Okada & Gray, 2023; Okada, 2025) can operate as an integrating axis between conceptual understanding, sociopolitical agency and community intervention, provided it is sustained by a systemic curriculum design that is structurally supported (Cortes, 2025; Perkins, 2009).

5.1 Pedagogical design and teacher transformation

The data from this study indicate that students' eco-externalised agency is mediated by a form of pedagogical teacher agency that combines critical reading of context, curriculum redesign and the strategic use of partnerships and technologies. In contrast to large-scale CONNECT studies that mapped patterns of student competences, the present work analyses in detail the accounts, decisions and dilemmas of six teachers, offering an operational explanation of how eco-externalised agency emerges. In doing so, the article shifts the focus from what students learned t ohow teachers orchestrate pedagogical conditions that make such learning possible.

The results point to seven interdependent pedagogical mechanisms that transform learning in contexts of inequality: (1) students' democratic choice with socioscientific argumentation; (2) encounters with experts in real-world contexts; (3) digital collaboration with families that integrates local knowledge; (4) authentic activities that generate social value and competences; (5) explicit attention to time constraints and prerequisites; (6) analysis of learning gains by teachers; and (7) analysis of learning gains by students. These mechanisms operationalise Perkins's notion of "playing the whole game" by avoiding "aboutitis" and content fragmentation, and by engaging students in complete socioscientific practices rather than decontextualised exercises (Perkins, 2009).

DOI http://dx.doi.org/10.23925/1809-3876.2025v23e73918

At the same time, these mechanisms enact Freire's pedagogy of problem-posing by shifting students from receivers of content to co-authors of inquiry, inviting them to read reality critically and act upon it (Freire, 1970). The structure also aligns with Hodson's socioscientific activism curriculum, which advocates learning trajectories oriented towards addressing socioscientific issues and engaging in responsible sociopolitical action (Hodson, 2014; Archer et al., 2012).

Collaborative digital tools support the complexity of these experiences by fostering participation and distributing cognitive load among students, teachers, families and experts, thus enabling greater focus on the design of integrated socioscientific investigations (OECD, 2019). In this scenario, CARE activates intrinsic motivation and values linked to sustainability and justice; KNOW develops conceptual competence and self-efficacy in AI and STEM; and DO mobilises concrete actions in school and community settings, making CARE–KNOW–DO work as a system rather than a linear sequence of activities (Carniel et al., 2024; Cortes, 2025).

Understanding pedagogical design as a system implies synchronising curricular, technological and organisational decisions to foster student agency oriented towards sustainability, justice and wellbeing, in line with critiques of banking education (Freire, 1970) and with proposals for socioscientific activism curricula (Hodson, 2014). This perspective aligns with current debates on open schooling, AI literacy and authentic assessment, which emphasise the need for problem-based projects that generate tangible benefits for students and their communities (Perkins, 2009; Gulikers, Bastiaens, & Kirschner, 2004; Lathouris, 2024).

In this study, eco-externalised agency (also referred to as eco-externalised or eco-outwards agency) is defined as the capacity to act beyond the classroom, mobilising AI and STEM to understand complex socio-environmental systems and to intervene collectively in favour of climate justice, sustainability and community wellbeing (Hodson, 2011; Archer et al., 2012). This notion brings together the opening of the school to the "real world", centred on people and planet, Freire's emphasis on critical reading of reality, and calls for science curricula committed to sociopolitical action (Freire, 1970; Hodson, 2014).

The data indicate three integrated characteristics of students' eco-externalised agency: (a) critical consciousness, evidenced by a shift from passive stances to active discussion of solutions for sustainability and equity, in line with problem-posing pedagogy (Freire, 1970); (b) systems thinking, expressed in the use of AI to visualise

DOI http://dx.doi.org/10.23925/1809-3876.2025v23e73918

relations between environmental data, policy decisions and local experiences (Perkins, 2009; Carniel et al., 2024); and (c) community response, manifested in the collaborative resolution of problems and in the co-construction of solutions with families (Archer et al., 2012). Taken together, these characteristics configure an outward-facing orientation that can inform future agency metrics in STEM and AI curricula committed to socioscientific activism (Hodson, 2014; OECD, 2019).

The temporal dimension proves central in extending Perkins's critique of fragmented learning, indicating that encounters with experts function as turning points that convert "aboutitis" into authentic epistemic practice (Perkins, 2009). After these encounters, concepts and data cease to be inert knowledge and start to operate as manipulable tools in real investigations, reinforcing the idea of legitimate participation in communities of practice (Hodson, 2011). Teachers report marked "before and after" moments: prior to meeting experts, students accumulated disconnected information; following dialogic validation by experts, the same information gained the status of resources for arguing, modelling and deciding in socioscientific contexts. This temporal structure suggests that learning the "whole game" requires carefully sequenced authentic encounters that render school activity recognisable as socially relevant practice, converging with evidence that authenticity, relevance and social recognition sustain motivation and persistence in STEM (Gulikers et al., 2004; Lathouris, 2024).

The implementation challenges observed relate less to individual teacher deficits and more to structural constraints associated with banking education and systemic barriers to authentic pedagogies in STEM and AI (Freire, 1970; OECD, 2019). Lack of time, rigid timetables, fixed prerequisite sequences and limited diversity in expert networks curtailed the depth of the experiences, even in the presence of strong teacher motivation and sophisticated local adaptations (Aldridge & McLure, 2024).
Rather than placing responsibility solely on teacher professional development, the findings point to the need for meso- and macro-level interventions – such as flexible timetabling, institutional review of prerequisites and expanded partnerships – if socioscientific activism curricula and AI literacy are to be implemented at scale (OECD, 2019; Aldridge & McLure, 2024). Theoretically, the study contributes by integrating whole-game learning, problem-posing pedagogy and socioscientific activism curricula through CARE–KNOW–DO (Perkins, 2009; Freire, 1970; Hodson, 2014); methodologically, by employing teacher-centred participatory action research (Cortes, 2025); and, in practice, by showing that pedagogical designs anchored in concrete

DOI http://dx.doi.org/10.23925/1809-3876.2025v23e73918

community challenges, co-designed with families and experts, can simultaneously develop AI competences, expand participation with equity and create authentic assessment forms with public consequences (Carniel et al., 2024; Gulikers et al., 2004).

5.2 Limitations and future research

The study's modest sample—six teachers, 330 students, three countries—limits statistical generalization, although replicated consistency across transnational, transdisciplinary, and transgenerational contexts strengthens confidence in the identified mechanisms and aligns with qualitative research standards. Future research should examine how the CARE–KNOW–DO choreography functions across diverse educational systems and countries; investigate which turning points matter most for different student populations and contexts; and develop tools to measure the quality of orchestration, rather than merely assessing the presence of elements.

The representation gaps identified—particularly homogeneous expert pools and insufficient indigenous knowledge integration—point to critical equity challenges requiring deliberate institutional commitments beyond curriculum design, consistent with literature on epistemic justice in science education. Subsequent iterations must centre *epistemic justice*: ensuring diverse experts, compensating community knowledge-holders, and validating local knowledge systems as legitimate science. This extends the vision of science education serving community empowerment rather than disciplinary gatekeeping (Hodson, 2014) and responds to calls in the literature for decolonizing science curricula (Gandolfi, 2021).

5.3 Recommendations for the open schooling movement at a critical turning point

The sample in this study – six teachers and 330 students in three countries – is deliberately modest, characterising an in-depth qualitative investigation. At the same time, the consistency with which the CARE–KNOW–DO model manifested across transnational, transdisciplinary and transgenerational contexts reinforces the credibility of the mechanisms identified, in line with trustworthiness criteria in qualitative research (Lincoln & Guba, 1985). Future studies should examine how this choreography

DOI http://dx.doi.org/10.23925/1809-3876.2025v23e73918

operates in different education systems, which turning points are most salient for distinct student populations, and under what conditions the pedagogical mechanisms sustain high-quality learning through educational orchestration, rather than through the mere replication of isolated elements of the model.

The representation gaps identified – particularly the participation of diverse experts and the integration of knowledge from local communities – highlight critical equity challenges that require institutional commitments beyond the curriculum itself. Subsequent iterations should prioritise epistemic justice (Fricker, 2007), ensuring diversity of voices, valuing community knowledge and recognising different knowledge systems. This extends Hodson's (2014) argument that science education should serve community empowerment and responds to calls in the literature for more inclusive and decolonial approaches to science curricula (Gandolfi, 2021).

5.4 Recommendations for the open schooling movement

Based on the findings of this study, it is possible to identify implications for the open schooling movement at a critical turning point. The data show that, although subsidised pilot initiatives can generate transformative experiences, their continuity and expansion depend on broader institutional and policy conditions, rather than on local pedagogical innovation alone.

In light of these findings, and in dialogue with the literature on the sustainability of educational innovation, the following recommendations are formulated as empirically derived from this set of cases, while potentially useful for other contexts in which open schooling faces increasing competition for funding. In particular, the results suggest that moving from isolated initiatives to institutionalised practices requires both stable local investment and the strategic positioning of open schooling within agendas such as AI education, teacher education, research and climate action (EU, 2024; UNESCO, 2021, 2024).

R1. Focus on three core mechanisms by developing guidelines and quality indicators for:

- students' democratic choice, leading to authentic outcomes
- just-in-time encounters with experts that legitimise inquiry
- family co-authorship mediated by simple digital tools that sustain complexity.

DOI http://dx.doi.org/10.23925/1809-3876.2025v23e73918

Rather than creating new models, the priority is to consolidate practices that are already tested and evidence-informed, as recommended by the literature on institutional amplification of educational innovations.

R2. Institutionalise open schooling by embedding it as a means of fulfilling existing institutional commitments such as public engagement, widening participation and knowledge exchange. In addition, policies should secure protected time for inquiry, flexible timetabling and authentic assessment arrangements. Institutionalisation supported by shared principles and routines creates the conditions for long-term sustainability.

R3. Present open schooling as a cross-agenda strategy, capable of responding simultaneously to calls in AI education, teacher development, researcher training and climate action, by emphasising authentic problem solving, ethical deliberation and climate citizenship. Framing open schooling in this way aligns with current funding priorities and with the literature on AI literacy, professional development and education for sustainability.

R4. Strengthen the evidence base with teacher-researchers by expanding:

- systematic reviews and project syntheses
- meta-analyses of outcomes
- methodological articles that detail implementation protocols
- case studies documenting impact and the expansion of practices.

Research on knowledge mobilisation indicates that consolidated evidence increases the capacity to influence policy and to compete for resources.

R5. Establish standards for epistemic justice by ensuring diversity among experts, providing fair compensation to community knowledge holders and recognising local and Indigenous knowledge systems as legitimate science, thus deepening the vision of science education oriented towards community empowerment. These measures respond to calls for equity-centred educational innovation and for decolonial approaches in science education.

6 FINAL REMARKS

This study provides evidence of methodological rigour by combining explicit coding oriented by theory and practice, systematic use of multiple data sources, and international comparative analysis anchored in teaching and learning dialogues with

DOI http://dx.doi.org/10.23925/1809-3876.2025v23e73918

the CARE–KNOW–DO model. The main theoretical contribution lies in the conceptualisation of students' eco-externalised agency, articulated with pedagogical design and teacher transformation as analytical constructs, positioning teacher-researchers as central pedagogical mechanisms in the emergence of AI competences. The results offer indications that the study addresses gaps at the intersection of AI, equity and education by mapping systemic barriers relevant to policy and suggesting possible cascading effects of teaching practices on student agency and broader processes of institutional change.

The analysis indicates that open schooling integrated with AI has the potential to mitigate epistemic fragmentation and to support forms of scientific citizenship when organised as a coherent choreography, rather than as a set of isolated and disconnected interventions. The CARE–KNOW–DO framework is proposed as an actionable structure; however, its effectiveness appears to be conditioned by systemic factors such as protected inquiry time, diverse partnerships and flexible assessment arrangements, which depend on policy decisions as much as on pedagogical innovation.

In light of global challenges associated with AI literacy, the findings suggest that approaches based solely on decontextualised technical training are limited, and that promising pathways lie in practices of authentic community problem solving in partnership with multiple actors. Such practices tend to position students as epistemic participants capable of contributing to collective futures, rather than as passive recipients of pre-defined solutions. In this sense, the sustainability strategy of the open schooling movement initiated more than two decades ago (Okada & Sherborne, 2006) is re-interpreted through this study, which highlights the relevance of authentic pedagogical responses to emerging priorities mediated by established expertise, community partnerships, authentic assessment and transformative learning opportunities.

The results converge with contemporary research indicating that more durable educational transformations tend to occur when there is coherence between pedagogical vision, organisational conditions and policy arrangements. By experiencing the "whole game" in contexts linked to the protection of people and the planet, students in this study appear to develop a set of transversal competences associated with eco-externalised inquiry, bringing together values, knowledge and action in situated projects. These indications suggest that combining open schooling,

DOI http://dx.doi.org/10.23925/1809-3876.2025v23e73918

STEM and equity-oriented AI may contribute to situated forms of student empowerment, without implying generalisations beyond the empirical scope investigated.

In these terms, the study provides evidence that such practices can speak to the four fronts highlighted in the introduction – the Sustainable Development Goals, climate action, socially oriented uses of AI and the strengthening of open schooling – supporting the formation of students who are better prepared to engage, in specific contexts, with present and future challenges. Taken together, these results position the CARE–KNOW–DO model as a reference framework for teacher education policies and for emancipatory AI pedagogies aligned with the 2030 Agenda.

ACKNOWLEDGEMENTS

I am grateful to be part of this celebration of PUC-SP CED Post-Graduation Programme, and Paulo Freire Research Group, which I had honour to be a member and completed by Doctoral studies on both Institutions including The Open University. We are very grateful to all CONNECT STEM teachers and students who participated in this study using, adapting, and creating AI open educational resources for open schooling. We thank the reviewers Tony Sherborne (UK) and Giorgios Panselinas (Greece); and to all our teachers' educators from Mastery Science School network in the UK, Regional Directorate of Primary and Secondary Education of Crete in Greece and COLEARN-Brazil.

FUNDING

This cross-national study is funded by the European Union part of the research programme Sustainability Education developed by the following projects: CONNECT—inclusive open schooling with engaging and future oriented science n. 872814 and involved PhD students' participants of METEOR n. 101178320.

DATA AVAILABILITY

ORDO Open University https://ordo.open.ac.uk/account/home#/projects/125821. CONNECT Science Platform: https://Connect-Science.net.

DOI http://dx.doi.org/10.23925/1809-3876.2025v23e73918

Curso: https://www.open.edu/openlearncreate/course/index.php?categoryid=367.

DECLARATIONS

This study was conducted in accordance with the Declaration of Helsinki and approved by the Human Research Ethics Committee of the UK, Greece, and Brazil. Informed Consent Statement Informed consent was obtained from the participants involved in the study.

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Recebido em: 04/11/2025

Aprovado em: 08/12/2025

Publicado em: 29/12/2025