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Beyond Access: Internet Connectivity and Educational Equity in Science Education

Konstantinos T. Kotsis [1*]

[1] Department of Primary Education, University of Ioannina, GREECE
* Correspondence: kkotsis@uoi.gr

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ABSTRACT

Internet connectivity can extend access to scientific resources, expertise, and collaborative inquiry, but equal provision does not ensure equitable educational opportunities. This conceptual article examines the conditions through which connectivity becomes a substantive opportunity to understand science, evaluate evidence, and contribute to inquiry. A critical, purposive synthesis of scholarship on digital inequality, scientific literacy, online evaluation, civic participation, and technology governance informs an integrated framework. It distinguishes four dimensions of access, material, usable, epistemic, and participatory, with accountable governance operating across them. The framework connects the scientific reasoning expected of learners with the resources, support, recognition, and protections institutions provide. Connected epistemic agency is proposed as an integrating educational aim encompassing learners' capacity to interpret scientific knowledge, evaluate evidence and expertise, and make justified contributions within digital and social networks. It is not presented as an empirically established construct distinct from existing competencies. A hypothetical school-connectivity case illustrates how the framework can inform comparisons between provision options by examining their consequences for differently situated learners. Implications are developed for curriculum, assessment, teacher education, and policy monitoring. The article offers a basis for locally informed design and empirical investigation, with particular attention to whether the framework identifies barriers and responses overlooked by existing approaches. Educational equity is evaluated through substantive opportunities for scientific learning and participation, alongside the distribution of institutional support and protection.

Keywords: educational equity, science education, internet connectivity, digital inequality, scientific literacy, epistemic agency

INTRODUCTION

Internet connectivity has become an important condition of participation in contemporary science education. It gives learners access to scientific explanations, simulations, observations, datasets, expert communities,

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and opportunities to communicate beyond the classroom. These resources can be particularly valuable where schools have limited laboratory equipment, specialist teaching, or access to scientific institutions. Yet the availability of a connection says little about whether learners can use these resources meaningfully. A school may be connected while students depend on shared phones, inaccessible interfaces, unfamiliar technical language, or teachers who receive little support for designing digital inquiry.

The resulting problem concerns educational equity. Equal access to a platform or device does not necessarily provide comparable opportunities to investigate a question, interpret a graph, challenge a misleading claim, or contribute to a group explanation. Students bring different experiences, languages, material circumstances, and forms of support to the same activity. Schools also differ in staffing, technical capacity, and institutional relationships. Connectivity interacts with these differences and can make established advantages more consequential. Research on digital inequality therefore directs attention beyond the binary distinction between connected and disconnected populations (Helsper, 2021; van Deursen & van Dijk, 2019).

Science education gives this issue particular significance. Scientific resources often assume conceptual knowledge, mathematical competence, and familiarity with disciplinary practices. A freely available research article may be less accessible to a learner than a carefully mediated classroom explanation. A sophisticated simulation can obscure the assumptions underlying its output. A public dataset can support inquiry only when learners understand what its variables represent and what conclusions its measurements permit. Equitable access to science requires opportunities to develop these interpretive resources as well as opportunities to reach information.

The civic purposes of science education extend the argument. Scientific knowledge informs decisions about environmental conditions, energy, health, and technology, although evidence alone does not determine acceptable policy. Scientific literacy includes the capacity to engage with such questions, consult appropriate expertise, and recognize the relationship between evidence and values (Feinstein, 2011; Kolstø, 2001; Roberts, 2007). When these capacities are unequally supported, differences in educational opportunity can become differences in whose questions are heard and whose contributions are regarded as credible. Democratic participation consequently remains relevant to the present argument as one important outcome of equitable science education.

The online information environment makes these demands more difficult. Scientific explanations circulate alongside commercial messages, advocacy, preliminary findings, and misinformation. Search rankings and recommendation systems influence visibility, while fluent generative artificial intelligence can produce explanations whose provenance is difficult to inspect. Scientific literacy in this setting requires learners to act as competent outsiders who can judge the relevance and credibility of expertise without pretending to reproduce all specialist research independently (Osborne & Pimentel, 2023). Students need explicit instruction and reliable networks to develop this competence.

This article addresses a diagnostic problem that connection statistics, generic digital-competence indicators, and assessments of scientific literacy cannot resolve when examined separately: students may possess a device, use an online dataset, and answer scientific questions correctly, yet have unequal opportunities to choose evidence, interpret measurement uncertainty, influence inquiry, or receive a reasoned institutional response. Conversely, apparent weaknesses in performance may arise from inaccessible interfaces, inadequate conceptual scaffolding, or restrictions on participation rather than from low learner ability. The study is needed because these mismatches can remain invisible when access, achievement, and participation are audited independently. Its question is therefore: under what educational and institutional conditions does connectivity provide substantively equitable opportunities for science learning and scientifically informed participation? The proposed contribution is an activity-level diagnostic framework linking four distinguishable access questions, material, usable, epistemic, and participatory, with accountable governance. Its added value is not a claim to have invented these dimensions, but a structured way to trace a science-specific

reasoning opportunity from the learner's actions to the institutional decisions that enable or constrain it. Connected epistemic agency denotes the conjunction of justified scientific decisions and real opportunities to enact and revise them in networked inquiry. A comparative application and a falsifiable research agenda specify how to examine whether this integration identifies barriers missed by existing approaches; no effectiveness or construct validity is claimed here.

CONCEPTUAL APPROACH AND SCOPE

This article offers a critical, purposive conceptual synthesis, not a systematic review or empirical study. Sources were selected for their capacity to explain a distinct step between technical provision and an equitable science-learning opportunity. Digital-inequality research addresses resources and conditions of use; scientific-literacy and inquiry scholarship addresses interpretation of claims, models, measurements, and evidence; civic and community science scholarship addresses the possibility of contributing to shared inquiry; and governance scholarship addresses institutional control over access, protections, and responses. Foundational theory supplies conceptual distinctions, empirical studies illustrate obstacles or teachable practices in specific settings, and policy reports locate responsibilities. No systematic database search, formal screening, or comprehensive quality appraisal was undertaken; the proposed synthesis cannot claim exhaustive coverage.

Framework construction followed four explicit analytical rules. First, retain a dimension only if it identifies an observable obstruction to an otherwise available science-learning activity. Second, distinguish obstructions that require different remedies: equipment and time (material), operational support (usable), disciplinary interpretation (epistemic), and consequential voice within inquiry (participatory). Third, classify institutional decisions about procurement, access rules, data protection, staffing, and response as cross-cutting governance rather than a fifth learner competence. Fourth, test each distinction against contrasting cases: a connected but conceptually excluded learner, a scientifically competent but unheard learner, and a learner whose participation imposes unequal privacy or home-resource burdens. The resulting four access dimensions are analytic lenses rather than ordered stages or statistically independent factors. The synthesis is judged by whether it leads to a different diagnosis or response, not simply by whether its categories resemble prior literature.

Scientific literacy supplies the disciplinary purpose of the synthesis: interpreting evidence and using science in social contexts (DeBoer, 2000; Roberts, 2007; National Academies of Sciences, Engineering, and Medicine, 2016). Community scientific literacy and epistemic networks situate those practices within relationships rather than isolated individuals (Busch & Rajwade, 2024; Feinstein & Baram-Tsabari, 2024). Kaliampos et al. (2023) provide a direct science-education antecedent by examining the knowledge needed for democratic engagement with disputes about mobile-phone radiation and telecommunications infrastructure. The present analysis asks an additional diagnostic question: which specific learning and institutional conditions permit differently situated pupils to conduct such evidence-based inquiry on comparable terms? This focus on the opportunity to perform disciplinary reasoning, not merely exposure to science information, guides the framework.

International reports are used to situate the argument and identify policy concerns, rather than as experimental evidence that connectivity causes learning gains. The International Telecommunication Union (2025) documents continuing inequalities in connectivity; UNESCO (2023a) examines the conditions and consequences of educational technology; and Boeskens and Echazarra (2025) distinguish the availability and educational use of digital resources. These sources address different populations and indicators. Their findings should not be combined into a single estimate of the causal effect of internet provision on science achievement.

The primary scope is school science education, with implications for initial teacher education and professional learning. Examples require adaptation to age, language, curriculum, and local infrastructure. The Wi-Fi case is an illustrative reasoning task concerning an institutional decision, not an intervention that has been implemented or evaluated. The framework offers questions for design and research; it does not establish that any particular configuration of connectivity will eliminate educational inequality.

EQUITY AND CONNECTIVITY IN SCIENCE EDUCATION

Equality of provision means identical entitlements, such as accounts, devices, or online time; equity means substantive opportunities to meet common scientific expectations despite differing barriers (Helsper, 2021; van Deursen & van Dijk, 2019). The relevant standard is not identical routes or identical scores, but comparable opportunities to formulate investigable questions, work with observations or data, justify explanations, account for uncertainty, and communicate conclusions (Feinstein & Baram-Tsabari, 2024; National Academies of Sciences, Engineering, and Medicine, 2016). Equivalent opportunity can be examined through the task's scientific demand, the support necessary to meet it, and each learner's opportunity to demonstrate the intended reasoning. Differentiated or offline routes are defensible when they preserve the same core cognitive work: for instance, a printed weather-data table may substitute for an inaccessible online display if pupils still select variables, compare observations, and justify an inference. An offline worksheet that merely asks pupils to copy conclusions is not equivalent to an online data investigation. Evidence of equity should consider variation in participation and work quality as well as average attainment; recognition, influence, and protection are relevant in addition to performance.

Consider a task requiring students to interpret an online climate dataset and prepare an explanation. The same link gives formal access to everyone. Some students may already know how to use spreadsheets and interpret uncertainty; others may be learning the language of instruction or using assistive technology that the interface does not support. A requirement to finish the task at home adds further differences in bandwidth, device availability, family assistance, and study time. Treating the task as identical for all does not make the opportunity to learn equivalent. The evaluation should therefore compare the scientific work made possible, not only the resources supplied. Teachers may vary language scaffolds, accessible representations, time, or response modes while retaining common criteria for the interpretation of evidence and the justification of claims. The crucial boundary is between assistance that makes reasoning possible and assistance that provides the conclusion. Differentiation is inequitable when some students merely reproduce answers while others design investigations, handle uncertainty, and defend explanations.

Equity also involves recognition. Learners' observations, community experiences, and languages can contribute to scientific questions without automatically establishing their causal explanations. A community's experience of poor air quality may identify an important problem and guide sampling, while estimating exposure or causal risk requires additional methods. Recognizing experience and evaluating evidence are compatible. The educational challenge is to avoid excluding a contribution because of its speaker's status while maintaining appropriate standards for the claim being made.

Participation provides a further dimension. Access to an explanation is different from being able to question it, contribute observations, or help decide what a class investigates. Civic science education highlights opportunities to move from understanding public problems toward purposeful participation (Levy et al., 2021). Rudolph and Horibe (2016) show that individual decision-making and civic engagement should not be treated as interchangeable. Equity in science education includes fair access to these forms of participation, although every lesson need not become a public action project.

The ethical foundation remains connected to the democratic argument for teaching science. Scientific institutions and technologies shape collective life, and those affected should have opportunities to understand

and question their uses. Rudolph (2020) emphasizes the moral purposes of science education, while Hodson (2003) connects scientific understanding to responsible social action. Empirical research illustrates the educational challenge underlying this commitment. Comparing 362 Greek pre-service teachers and 425 primary school students, Tsoumanis et al. (2023) found that prospective teachers performed significantly better, although demonstrated scientific literacy remained low in both groups. Within the present framework, these findings reinforce the need to support scientific literacy throughout schooling and teacher preparation. Scientific literacy is consequently treated as a democratic educational entitlement whose realization requires sustained opportunities to develop scientific understanding and reasoning. Equity therefore extends beyond achievement scores to opportunities for informed voice and collective inquiry, without requiring political agreement as an educational outcome.

Connectivity can reduce geographic distance from scientific resources. A rural school can consult an expert, examine satellite observations, or participate in a shared environmental investigation. Open resources can supplement a small school library, and remote professional communities can support teachers who lack local specialist colleagues. These opportunities are educationally significant when they give students access to concepts, practices, or relationships that would otherwise be difficult to obtain. Their value depends on how they are incorporated into teaching. The relevant unit of analysis is consequently the learning activity rather than the connection alone. Watching a video, operating a simulation, interpreting a dataset, and collaborating with researchers impose different technical and conceptual demands. A phone may be adequate for reading a short explanation but poorly suited to comparing several graphs or producing an extended data analysis. Van Deursen and van Dijk (2019) demonstrate why differences in material access persist beyond basic internet availability. Device quality, autonomy of use, and support remain relevant after connection rates improve.

Institutional differences can amplify these inequalities. Schools with stable staffing and technical assistance may use connectivity for sustained inquiry, while those with unreliable systems may restrict it to teacher demonstrations. Such differences should not be interpreted as differences in teacher aspiration or student ability. They reflect what institutions make feasible. Helsper (2021) places digital inequality within broader social circumstances, which suggests that equitable policy must address the interaction between educational and social conditions rather than expecting technology to compensate automatically for disadvantage.

International policy provides compatible cautions. UNESCO (2023a) treats equitable access, appropriate governance, and teacher preparation as important conditions of educational technology. The European Commission (2020) situates inclusive digital education within a wider system of institutional capacity. DigComp 2.2 defines competence across information and data literacy, collaboration, content creation, safety, and problem solving (Vuorikari et al., 2022). In science education, these dimensions need to be connected to subject knowledge and the evaluation of scientific claims. More frequent technology use should not be equated with better opportunity. The OECD analysis by Boeskens and Echazarra (2025) supports attention to the quality and context of digital resource use. An equity evaluation should therefore ask whether connectivity expands access to worthwhile scientific thinking. It should also examine what technology displaces. If an online activity reduces time for practical investigation or replaces accessible discussion with difficult independent reading, its distributional effects may be adverse even when students are technically connected.

AN ACTIVITY-LEVEL FRAMEWORK FOR EQUITABLE CONNECTED SCIENCE EDUCATION

The unit of analysis is a specific science-learning activity, not a device or a school-level connectivity total. Four access dimensions identify distinct potential failure points: material access (can the learner undertake the task with adequate tools and time?), usable access (can the learner operate the resource and representations?), epistemic access (can the learner interpret and critically use scientific evidence?), and

participatory access (can the learner make choices, contribute reasoning, and receive consideration?). Accountable governance shapes all four through decisions about support, accessibility, procurement, privacy, and response. Their boundaries are diagnostic rather than exclusive. Science-specific epistemic access particularly involves relating measurement to a quantity and its uncertainty, distinguishing observations from explanatory models, evaluating experimental or sampling design, identifying variables and controls, and judging whether a claim follows from data. A usable interface may permit graph navigation without enabling these disciplinary judgments. Conversely, a pupil may reason well about an experiment but lack a legitimate role in choosing the question or presenting the findings. This contrast gives the framework a more demanding test than counting logins or judging generic information skills alone.

Material access includes reliable connectivity, suitable devices, accessible interfaces, maintenance, and sufficient time and space for use. It also includes arrangements that keep essential learning available during outages or when home access is restricted. A school should not assign an online-only science task without considering whether learners can complete it under reasonable conditions. Offline resources can protect continuity, provided they offer comparable intellectual opportunities rather than a reduced curriculum.

Usable access concerns the capacity to operate tools purposefully. Students need opportunities to formulate searches, organize files, navigate data displays, communicate appropriately, and protect personal information. These skills are not guaranteed by familiarity with entertainment or social media. Breakstone et al. (2021) document substantial difficulties in students' evaluation of online information. DigComp 2.2 offers a broad vocabulary for these competencies, but science-specific instruction is needed to relate them to inquiry and evidence (Vuorikari et al., 2022).

Epistemic access requires opportunities to perform the characteristic reasoning of science: decide what a measurement represents, inspect scale and uncertainty, relate data to a scientific model, consider alternative explanations, and evaluate whether methods warrant a causal or descriptive claim. In a weather inquiry, reading the graph is operational; distinguishing temperature variation from a long-term trend, recognizing missing observations, and avoiding unwarranted causal inference are epistemic. In an online simulation, operating the sliders is usable access; explaining the model assumptions and assessing whether its output is corroborated by measurements is epistemic access (Feinstein, 2011; Osborne & Pimentel, 2023). These requirements give the framework disciplinary specificity while allowing that analogous questions can arise in other subjects.

Participatory access concerns opportunities to ask questions, contribute observations, challenge interpretations, and communicate with relevant audiences. In group inquiry, this includes meaningful roles for students whose language or confidence may limit spontaneous participation. Beyond the classroom, it includes accessible channels through which institutions receive and respond to learners' work. A public-facing project can still be inequitable if only confident students speak, if families must supply unpaid time, or if assessment rewards social connections rather than scientific reasoning.

Accountable governance concerns procurement, data practices, accessibility, algorithmic mediation, and institutional response. Learners generally cannot negotiate the terms of a required educational platform. Schools and authorities therefore carry responsibility for protecting privacy, providing support, scrutinizing consequential automated decisions, and maintaining alternatives where necessary. UNESCO (2023b) emphasizes human agency, privacy, and validation in the use of generative AI. Kotsis (2025) further examines privacy, data security, and algorithmic bias in educational AI, emphasizing informed consent and transparency in the collection and processing of personal data. Within the present framework, these concerns connect accountable governance with the protection of learners' data rights and scrutiny of potentially unequal treatment. Kotsis and Stylos (2026) also connect transparency, accountability, and human oversight with pedagogy, assessment, and teacher agency in AI-supported STEM education. Their analysis supports treating institutional governance and teachers' professional judgment as interconnected conditions of responsible

technology use. These concerns are part of equitable provision because the costs and risks of compulsory systems are not always distributed evenly.

Table 1 summarizes these conditions and examples of evidence that could inform a local audit. The indicators are proposed design aids, not validated measures. Interpretation requires consultation with students, families, teachers, and relevant support staff. A formally accessible platform may still create barriers in practice, while a flexible local arrangement may succeed despite limited infrastructure. The purpose is to identify and remove obstacles without attributing institutional failures to individual learners.

The conditions interact. Better equipment may expand the tasks a learner can attempt, but conceptual scaffolding determines whether those tasks become intelligible. Source-evaluation instruction may strengthen judgment, but available languages and institutional networks influence which sources students can consult. Participation may develop agency, but unsafe platforms can make that participation costly. The framework therefore supports examining configurations of provision rather than assigning each school a single connectivity score. Access to scientific information can widen opportunities while making evaluation more demanding. Online sources can use graphs, references, technical vocabulary, or images of laboratories to project authority. Students need to distinguish these signals from the quality of the underlying evidence. The National Academies of Sciences, Engineering, and Medicine (2025) situates science misinformation within interacting social and technological systems. This perspective helps avoid treating misleading content as a problem that can be solved through individual vigilance alone.

The scientific problem is not merely whether a website appears credible, but whether the evidence warrants the specific claim. Kolstø (2001) and Allchin (2023) identify the importance of examining scientific knowledge claims, while Bencze et al. (2020) relate such evaluation to science-in-context. For a claim drawn from an environmental study, learners should ask how variables were measured, what the comparison group represents, whether uncertainty and confounding factors were considered, and how far the conclusion generalizes. These questions provide the disciplinary bridge from online evaluation to scientific argumentation.

Lateral reading provides a useful first move: identify who stands behind a source, trace a scientific claim to its original study or authoritative synthesis, and compare independent accounts (McGrew, 2020; Wineburg et al., 2022). Instructional findings from civic online reasoning establish the teachability of these source checks, not their automatic transfer to science learning.

Table 1. Conditions and proposed indicators for an equity audit

Condition	Barrier to opportunity	Possible evidence and response
Material access	Unreliable connections or unsuitable devices	Document task completion conditions; provide suitable devices, maintenance, and equivalent offline routes.
Usable access	Tools assume skills that have not been taught	Observe navigation and search; explicitly teach operations and provide accessible technical support.
Epistemic access	Information is reachable but not intelligible	Examine explanations and graph interpretations; supply conceptual, linguistic, and representational scaffolds.
Participatory access	Contribution follows confidence, status, or outside support	Record roles and audience response; structure turns, offer varied contribution modes, and build institutional channels.
Accountable governance	Required systems impose opaque decisions or unequal risks	Audit accessibility, data practices, and appeals; require transparency, human review, and feasible alternatives.

That transfer requires an additional step in which pupils scrutinize the study's measurements, design, uncertainty, and evidential limits. A source can be reputable yet offer evidence insufficient for the question under discussion.

Scientific knowledge and evaluation strategies should be taught together rather than treated as interchangeable (Dabran-Zivan & Baram-Tsabari, 2025; Sharon & Baram-Tsabari, 2020). An appropriate assessment distinguishes three judgments: source provenance, methodological warrant, and interpretation of the scientific finding. A student who correctly identifies a trusted organization but cannot explain a graph's uncertainty has demonstrated only part of the intended competence. Such distinctions avoid equating a successful search with sound scientific judgment.

An equity perspective asks who receives this instruction and under what conditions. Independent online research can reward students who already possess domain vocabulary, reliable networks, and time to compare sources. Teachers can reduce these barriers by modelling a search, providing an initial accessible source set, and gradually increasing independence. The support should make reasoning visible rather than preselect every conclusion. Assessment should distinguish difficulties with reading or interface use from difficulties in evaluating evidence.

Trust also has a social distribution. Students and families may differ in their access to scientists, librarians, health professionals, or community organizations. Feinstein and Baram-Tsabari (2024) explain why epistemic networks matter for public engagement with science. Schools can broaden these networks by making consultation with relevant expertise part of ordinary learning. They should also explain why a source is appropriate to a question, how conflicts of interest can be examined, and what correction practices make trust warranted.

Collective reasoning can complement individual evaluation. Feinstein and Waddington (2020) emphasize purposeful sensemaking rather than relying exclusively on isolated truth judgments. Students can compare interpretations, identify missing evidence, and consult different forms of expertise. Teachers need to structure these exchanges so that authority does not simply follow confidence, fluency, or social status. Recognition of different experiences must be combined with standards that distinguish relevant observation from unsupported causal inference.

Generative AI adds opportunities for translation, accessible explanation, and alternative representations, alongside risks concerning provenance, bias, and privacy (UNESCO, 2023b). Equity requires examining whether tools give all students access to deeper understanding or distribute unequal forms of assistance. A student should not be confined to simplified automated explanations while peers receive human discussion and inquiry. Important assertions produced by AI require checking against traceable evidence, and schools should provide routes for questioning or correcting outputs.

SCIENTIFIC EVIDENCE EVALUATION AND CONNECTED EPISTEMIC AGENCY

Connected epistemic agency is used here as a relational, task-level educational aim: learners can make and justify scientific choices and are genuinely permitted to use those choices in a connected investigation. It is not offered as a newly validated psychological trait. Its observable indicators include proposing a testable question, selecting or challenging relevant measurements, articulating the limits of a model or dataset, consulting suitable expertise, revising an inference in response to evidence, and making a contribution that others must consider. Mere source location, accurate recall, or visible participation is insufficient. The diagnostic focus is the fit, or mismatch, between demonstrable reasoning and the institutionally available opportunity to exercise it.

The term is deliberately bounded by prior scholarship. Scientific literacy names the substantive disciplinary and civic understanding; digital competence includes operation and evaluation of digital tools; and community scientific literacy and epistemic-network accounts foreground distributed resources and expertise (Busch & Rajwade, 2024; Feinstein & Baram-Tsabari, 2024; Vuorikari et al., 2022). Connected epistemic agency does not replace these accounts. Its potentially useful additional question is whether a learner who can reason scientifically can also exercise consequential choices within a particular connected activity, and which institutional constraints prevent that exercise. If independent assessments of scientific literacy, participation, and digital inequality already yield the same diagnostic finding and response, the new label adds no demonstrated explanatory value and should be revised or abandoned.

Two pupils may give equally accurate explanations of a dataset while only one can decide which measurements to compare or present a justified objection to the group. Conversely, a pupil with an assigned speaking role may lack access to the representations needed to assess a claim. Ordinary achievement or attendance measures can miss these contrasting cases. An activity-level audit would document both the quality of each pupil's evidential decisions and the actual opportunities to make, challenge, revise, and communicate them, then identify whether the barrier is epistemic, participatory, operational, material, or institutional. This is a proposed diagnostic gain, not a proven distinction.

The framework distinguishes learner capabilities from institutional obligations. A student can develop stronger evaluative practices while continuing to face inaccessible resources or discriminatory responses. Such barriers should not be interpreted as a failure of agency. Conversely, an institution can provide accessible resources without ensuring that students learn to evaluate claims independently. Evidence from teacher education reinforces the importance of conceptual preparation: in a questionnaire study involving 427 prospective primary and secondary teachers, Gavrilas and Kotsis (2023) found insufficient knowledge of electromagnetic radiation and its applications in wireless technologies. Within the present framework, this finding supports explicit attention to the scientific understanding teachers need to guide informed inquiry into connectivity-related questions. Equity requires attention to both what learners can do and what institutions allow and support them to do.

Community scientific literacy provides a useful complement. Busch and Rajwade (2024) locate scientific capability in relationships among people, resources, purposes, and contexts. A class collaborating with residents and a university may investigate a local environmental question more effectively than any student working alone. The relevant equity question concerns access to this collective capacity. Schools with fewer established partnerships should receive support to build them, rather than having weaker networks treated as an unavoidable local limitation.

The framework also preserves civic participation without making a preferred political outcome its criterion of success. Students may investigate shared evidence and disagree about priorities or acceptable trade-offs. Learning should be evaluated through conceptual accuracy, evidential reasoning, recognition of uncertainty, and responsiveness to others. A school council's rejection of a student proposal does not necessarily show educational failure, while acceptance does not validate weak evidence. A reasoned institutional response is valuable because it allows learners to understand how their contribution was considered.

Table 2 proposes observable evidence that may be considered alongside separate records of opportunity and support. A fair assessment asks not only whether the learner reasons well, but whether the learner had access to a meaningful choice and whether that contribution was considered. The indicators are examples, not validated scales; the same core scientific demands must remain in place across accessible response formats.

Table 2. Connected epistemic agency and equitable assessment

Capability	Evidence of learning	Support for a fair opportunity
Orientation	Defines a question and locates relevant resources	Teach search strategies and provide accessible starting resources.
Evidential judgment	Relates claims to methods, data, and uncertainty	Scaffold scientific vocabulary and data interpretation without supplying conclusions.
Networked sensemaking	Consults relevant expertise and revises an interpretation	Provide shared access to experts and clarify the role of different kinds of knowledge.
Deliberation	Distinguishes evidence from values and responds to others	Use preparation time, structured discussion, and varied response modes.
Contribution and reflection	Produces an accurate contribution and interprets the response	Provide an authentic audience; assess reasoning and reflection rather than policy success.

COMPARING SCHOOL CONNECTIVITY DECISIONS

A school Wi-Fi decision illustrates the difference between technical provision and science-learning opportunity. Internet service, wireless exposure, device use, and screen time are distinct questions; a choice among wired and wireless options is neither a direct measure of scientific learning nor, by itself, a health-risk evaluation. The case is hypothetical and is not evidence of the framework's effectiveness.

Science preparation must distinguish ionizing from non-ionizing radiation, exposure conditions, and the limits of particular findings; misconceptions about electromagnetic radiation have been documented among prospective teachers (Gavrilas & Kotsis, 2023, 2024). Scientific engagement also should not be equated with demonstrated understanding (Stylos et al., 2023). The International Commission on Non-Ionizing Radiation Protection (2020) provides exposure guidelines, while technical compliance and policy decisions remain responsibilities of qualified authorities, not outcomes to be inferred from classroom debate.

Karipidis et al. (2024) synthesize human observational evidence concerning selected cancer outcomes from radiofrequency exposures; that synthesis must not be represented as a direct experiment on every school Wi-Fi installation or a guarantee about all possible effects. Students can learn to match a claim to the studied exposure, population, outcome, and uncertainty rather than adopt either an unsupported assurance or an unsupported allegation of harm.

Knowledge, attitudes, and precautionary behaviour must be distinguished. Gavrilas et al. (2022) found incomplete knowledge and a mismatch between risk attitudes and self-reported behaviours in a questionnaire study of 619 university students. A school therefore should not use reported concern as a proxy for scientific understanding. Instead, it should provide accessible evidence, enable questions from families, and examine the unequal educational consequences of each connectivity option.

Consider a hypothetical school of pupils aged 11–12 using online weather observations to investigate a local environmental question. Some share devices or depend on school access; others need language or accessibility support, and families raise questions about wireless exposure. The school considers retaining the existing arrangement, improving Wi-Fi with a device-loan scheme, or expanding scheduled wired workstations.

A conventional evaluation might record network availability, device counts, logins, and bandwidth. These metrics could register improved provision even if some pupils can only copy graphs, lack time to analyze

measurements, or never influence the question investigated. The proposed framework asks additional, activity-specific questions: who can access data during school hours, operate representations, interpret measurement and uncertainty, justify an inference, and contribute to a decision? It also asks who must provide translation, accessible formats, teaching time, data protection, or a response to student evidence. The contrast is summarized in **Table 3**; its entries are diagnostic predictions to investigate, not observed results.

The comparison changes the decision criterion without dictating a single technology. Wider Wi-Fi coverage may improve availability but leave conceptual and participation barriers untouched; scheduled wired stations may work if all pupils receive sufficient time for substantive investigation. A pupil's evidence-based briefing should be assessed for its selection and interpretation of data, treatment of uncertainty, and consideration of alternatives, not agreement with a preferred institutional decision. Exposure compliance must remain with competent specialists. Consultation should offer accessible summaries, translated materials where practicable, paper responses, and in-person opportunities so that families without reliable connectivity can contribute. Questions about health and educational access deserve respectful consideration, while factual explanations remain subject to evidential scrutiny.

Students could submit an accessible briefing, and the school body could explain how its evidence and proposals were considered. The framework adds a second evaluative question beyond whether an option improved connectivity: did differently situated pupils gain comparable opportunities for valid scientific reasoning and meaningful participation? Answering this would require classroom and institutional data; the hypothetical case alone cannot establish an effect.

CURRICULUM, ASSESSMENT, TEACHER PREPARATION, AND POLICY

An equity-oriented curriculum should give all learners sustained opportunities to connect scientific concepts with evidence in use. Core knowledge remains essential. Students cannot evaluate many claims about climate, infection, or telecommunications without understanding relevant mechanisms, quantities, and representations. Source evaluation should therefore be taught within scientific inquiry rather than added as a generic checklist detached from subject learning. The PISA 2025 science framework similarly connects scientific competencies with reasoned engagement and action (OECD, 2025). Teachers can begin with shared investigations that reveal the reasoning required before introducing independent online work. A lesson might compare two graphs of the same observations, examine how a press release represents a study, or trace a claim from a social-media post to an institutional synthesis. Carefully chosen contrasts allow students to attend to relevant differences without requiring unrestricted browsing. Subsequent tasks can expand choice as students acquire strategies and conceptual confidence.

Table 3. Contrasting technical and science-equity diagnoses in the hypothetical case

Evaluation focus	Conventional connectivity audit	Activity-level science-equity audit
Resource	Counts devices, access and bandwidth	Checks adequate time, accessible formats, and feasible offline equivalence
Learning	Records logins and task completion	Examines measurements, model assumptions, uncertainty and evidence–claim warrant
Voice	Counts submissions or survey responses	Checks who chooses questions, challenges inferences and receives a reasoned response
Responsibility	Recommends technical upgrades	Assigns instructional, accessibility, privacy and governance responses

Differentiation should preserve the scientific question. Students can receive glossaries, audio explanations, captioned demonstrations, accessible data formats, or additional time while examining the same relationships. A translated summary may open access, but its scientific meaning needs checking. Simplification should remove unnecessary linguistic difficulty without erasing uncertainty or replacing a mechanism with a misconception. Support should be adjusted in response to evidence of understanding rather than assigned permanently on the basis of background. Practical work and digital resources should be coordinated. A simulation can support comparison of variables that are difficult to control physically, while direct observation can expose measurement and material constraints. Equity does not require maximum screen use. It requires selecting combinations of tools that make important reasoning available to learners. Where technical access is limited, schools should protect opportunities for substantive inquiry rather than substituting passive content consumption.

Collaborative activities require attention to role distribution. One student operating the device can unintentionally control the investigation and its interpretation. Rotating roles and recording individual reasoning can help reveal who is learning from the task. Teachers should observe whether students have opportunities to propose questions, interpret results, and challenge explanations. A visually polished group product offers weak evidence of equitable participation unless the process is also considered.

Assessment should examine scientific reasoning alongside the conditions under which students can demonstrate it. In the proposed weather-record investigation, common criteria could address the interpretation of variables, the justification of comparisons, and the recognition of uncertainty. Material and usable access require suitable equipment, sufficient school time, and support with navigation so that performance does not depend on home connectivity or familiarity with a particular interface. Epistemic access requires accessible representations and clarification of task language while preserving the reasoning students must undertake themselves. Participatory access requires evidence of each learner's contribution, since a polished group briefing may conceal unequal opportunities to interpret data or influence conclusions. Annotated graphs, oral explanations, and written accounts can provide alternative ways to demonstrate the same intended understanding. Governance adds responsibility for appropriate data handling and review of assessment decisions. These arrangements distinguish support that enables students to express their reasoning from assistance that supplies the reasoning being assessed.

Open-web performance tasks can complement assessments of core knowledge. Students can record a search path, justify source selection, and explain a provisional judgment. McGrew (2020) and Wineburg et al. (2022) support the teachability of evaluative practices, although assessments must be adapted to their local purpose. When AI assistance is permitted, the task should require explanation of which claims were checked and how tool contributions affected the final account. The quality of reasoning should remain visible. Teacher education is an institutional requirement of the framework. Initial preparation and professional learning should combine subject knowledge, accessible design, online verification, and facilitation of socioscientific discussion. Where AI mediates learning and assessment, preparation should also develop critical AI literacy and the capacity to exercise informed professional judgment. Kotsis and Stylos (2026) emphasize teachers' roles in evaluating AI contributions, maintaining human oversight, and assessing students' reasoning processes alongside final products. Teachers need time to evaluate resources and access to librarians, technical staff, and scientific partners. Professional preparation should also address the data practices of AI-supported resources, including privacy, informed consent, transparency, and potential algorithmic bias (Kotsis, 2025). In the present framework, this entails opportunities to examine what learner information a tool collects, how it is processed, and what institutional protections are available. Teachers should not be expected to compensate privately for structural deficiencies. Professional judgment also includes deciding when a digital activity offers little educational value or imposes unnecessary burdens.

Equitable connectivity requires sustained provision rather than isolated equipment purchases. Funding should consider reliability, maintenance, accessibility, staffing, and support alongside installation. Rurality, socioeconomic disadvantage, disability, and language circumstances may change the resources needed to provide comparable opportunities. Equal funding per device is consequently an incomplete expression of fairness. The appropriate question is what provision a school requires to sustain worthwhile science learning for its students.

Policy monitoring should examine whether improvements in provision expand substantive learning opportunities for students facing different barriers. The framework suggests examining whether learners can complete essential science activities using suitable resources, operate the required tools, interpret the scientific content, and contribute meaningfully to inquiry. Institutional review should also consider accessibility, data practices, and responses to reported difficulties. These dimensions should remain distinguishable rather than being combined prematurely into a single equity score. Evidence could include task-completion conditions, work samples, observations of participation, and student and family accounts, with comparisons across relevant groups where ethically and practically appropriate. For example, an increase in average task performance would provide incomplete evidence of improvement if students dependent on school devices continued to receive less investigation time or fewer opportunities to interpret data. Monitoring should therefore identify who benefits, which barriers persist, and what institutional response follows. The proposed indicators require local development and evaluation; they are not established measures of educational equity.

Procurement decisions should protect educational autonomy. Contracts should address data minimization, accessibility, portability, support, and the possibility of leaving a service. Schools should be able to explain consequential automated decisions and offer human review. Learners with limited alternatives should not have to accept disproportionate surveillance as the price of curriculum access. The concerns raised in UNESCO's guidance on generative AI apply here to the distribution of both opportunities and risks (UNESCO, 2023b). Public scientific institutions also have responsibilities. Open publication should be accompanied, where feasible, by understandable explanations, accessible datasets, and clear accounts of uncertainty. Schools with fewer professional contacts need channels for consulting appropriate expertise. Partnerships should be structured so that well-connected institutions do not receive all enrichment opportunities. Reciprocal arrangements can allow community questions to inform projects while scientists help clarify what the evidence can support.

Civic participation needs institutional response. Levy et al. (2021) identify the potential and uncertainties of civic science education, and Rudolph and Horibe (2016) clarify its different forms. Policy can support modest opportunities for authentic engagement through school bodies, municipalities, museums, or scientific organizations. These partners should explain the limits of their commitments and respond to student contributions. Invitations that repeatedly produce no response can reproduce the experience that participation is reserved for those with established influence.

Governance must also address trade-offs. Strong filtering can protect students while excluding useful information; standardized platforms can simplify support while limiting accessibility or institutional choice; and remote collaboration can widen participation while introducing new demands. Decisions should identify affected groups, criteria, evidence, and review arrangements. Equitable provision is a continuing process of adjustment rather than a property secured permanently by selecting a particular technology.

LIMITATIONS AND RESEARCH DIRECTIONS

The framework does not establish that internet connectivity causes equitable learning or that the five conditions are sufficient to secure it. It integrates selected scholarship and policy sources, predominantly in

English, and may not capture how inequality is understood in every educational setting. Its categories overlap, and their relevance may vary with age, subject matter, language, and local institutions. Research should examine whether the distinctions support useful diagnosis rather than assuming that conceptual coherence guarantees practical value.

A first research priority is to operationalize opportunity at the level of learning activities. Classroom studies could document device access, teacher scaffolding, student roles, and the scientific reasoning visible in work samples. Comparisons should examine whether apparently similar digital tasks offer different intellectual demands to different groups. Such studies need attention to within-school variation, because average school provision can obscure substantial differences in students' experiences. A second priority is to evaluate targeted support. Research could examine whether accessible representations, explicit source evaluation, or structured expert consultation improve particular outcomes and for whom. Pre-intervention differences and implementation conditions would need to be documented. Where feasible, designs should compare credible alternatives and use measures appropriate to the intended construct. Improvement after an activity alone would not establish that connectivity or the proposed framework caused the change.

A third priority concerns participation and governance. Studies could trace how student contributions are received and whether institutional responses are understandable and consequential. Participatory research can include students and families in identifying barriers, while independent analysis protects against treating satisfaction as evidence of scientific learning. Privacy-preserving audits could investigate whether required platforms distribute costs or risks unevenly. Institutional change should be examined alongside student competence. A concrete comparative study could sample classes completing the same inquiry into online weather observations and undertake two parallel audits. Audit A would apply standard indicators of connectivity and digital use (device availability, bandwidth, access time, navigation, and task completion). Audit B would retain these measures and add observations of measurement interpretation, model-based explanation, treatment of uncertainty, actual student choices, contribution uptake, accessibility, and institutional response. Assessors should specify coding rules and disagreements in advance, compare diagnoses and recommended remedies for the same pupils, and examine inter-rater agreement. A particularly discriminating test would identify learners with similar scientific understanding and technical access but different chances to select evidence or influence the investigation. The framework has incremental diagnostic utility only if Audit B consistently reveals consequential barriers or justified responses that Audit A, and a comparison using established scientific-literacy and participation constructs, misses. Replication across settings and disconfirmation are essential; such findings would not independently validate a new psychological trait or demonstrate causal learning benefits.

The scope of responsibility also needs care. Science teachers cannot resolve poverty, commercial platform incentives, or every form of exclusion. A framework that asks them to do so would obscure structural accountability. The proposed approach instead connects classroom design to responsibilities at institutional and policy levels. Educational equity remains an ethical commitment and a matter for public judgment; empirical research can clarify consequences and mechanisms without determining every normative choice.

CONCLUSION

Internet connectivity can widen science-learning opportunities, but connectivity statistics and achievement averages alone cannot establish that learners have equivalent chances to conduct inquiry. A learner may reach a dataset without being able to interpret its measurements or uncertainty; another may reason accurately without a meaningful opportunity to select evidence, challenge a model, or communicate findings. The article responds to this diagnostic gap by specifying which features of a science-learning activity and its institutional setting need to be examined together.

The proposed contribution is a testable activity-level analytic procedure: distinguish material, usable, epistemic, and participatory access; inspect governance responsibilities across them; and compare learners' justified scientific choices with the opportunities to enact those choices. Its science-specific contribution is to make experimental and observational reasoning, measurement, modeling, evidence–explanation links, uncertainty, and warranted claims central to assessing what connectivity affords. Connected epistemic agency is a provisional name for this alignment, not a demonstrated separate competency. The comparative school-connectivity case identifies questions that conventional technical indicators may overlook, without claiming empirical superiority. The framework may help teachers protect the intellectual demand of differentiated and offline tasks, help institutions diagnose barriers to informed participation, and guide empirical comparisons with established approaches. Its usefulness remains unproven. A convincing next test is whether it reliably detects remediable inequities that otherwise go unnoticed, particularly among learners least well served by digital provision.

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