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Leadership Strategies for Leveraging Digital Learning Technologies to Improve Science Achievement Among Underrepresented Students in Secondary Education

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Abstract

Digital learning technologies have come to be central to secondary science education and, if they are to make an educational difference, school leadership must not simply put digital resources into teachers' hands, but must also engage with deeply embedded inequities in access and participation in digital learning. Existing literature tends to focus on leadership, technology integration, science learning, and educational equity, which may be separate domains with little understanding of their interactions in practice. This study explores secondary science teachers' experiences with leadership strategies that support digital learning and equitable science-learning opportunities for underrepresented students. A multi-site qualitative descriptive design was used with 20 purposively selected science teachers from five public secondary schools in Lynchburg, Virginia; each school had a single semi-structured focus group interview. Through reflexive thematic analysis, five themes emerged: distributed leadership as the professional influence, leadership support for digital science learning, technology as an amplifier of scientific inquiry, equity by design and perceived science-learning outcomes. Participants emphasized meaningful involvement in decision-making, science-specific professional support, reliable infrastructure, accessibility, and purposeful technology–pedagogy alignment. The study integrates leadership, enactment of digital science and equity in one coherent narrative, contributing to an interpretive understanding of learning and equity stewardship. The findings indicate that an impactful and fair digital transformation is driven less by the use of technology, and more by leadership that promotes quality of learning, accessibility, participation, and equitable science-learning opportunities.

Keywords: Distributed Leadership, Digital Learning Technologies, Science Education, Educational Equity, Underrepresented Students, Secondary Education.

1 Introduction

Digital transformation has become a hallmark of modern secondary schools, affecting the organization of instruction, how teachers are supported, and the opportunities available to students to access knowledge across disciplines. Digital technologies in science education can extend and enhance learning experiences through an interactive, visual, collaborative, and enquiry-based approach that is not readily achievable with traditional teaching. While the frequency of technology use is crucial, empirical evidence has shown that digital technologies also enhance engagement, motivation, conceptual understanding, and achievement in school science when appropriately adopted, as opposed to merely when used more often (Ateş & Köroğlu, 2024; Consoli et al., 2024; Zafeer et al., 2025). These developments position school leaders as a key organizational determinant of the success or failure of meaningful digital transformation in education.

However, access to technology does not guarantee high-quality or equal science learning. Some challenges may include inadequate infrastructure, limited professional development, a lack of digital competence among teachers, weak technical support, and the inability to adapt technology to the pedagogies employed (Park et al., 2023). These limitations can have significant implications for certain groups of learners, one of which, in the present study, is defined as learners who are historically situated in lower-echelon positions and/or socially marginalized and therefore face restrictions on their participation and opportunities in science. The research on Science Equity demonstrates that attention to access to science content is

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not sufficient to ensure a meaningful opportunity to learn, but that the science classroom must address students' identities, experiences, participation, and relationships. (Kang, 2021; Rüschenpöhler, 2024). Research also highlights the digital divide's impact on students' access to technology and digital skills, which can limit engagement and learning for underserved students (Nguyen, 2025).

Recent research increasingly positions leadership as a critical link between technology and classroom instruction. Strategic vision, professional development, resource provision, instructional supervision, collaboration, and capacity building are among the ways school leaders influence technology integration (Adewale, 2025; Danganan & Gamboa, 2025; Karakose et al., 2024). A distributed perspective also implies that this is not solely a principal's job; leadership can be expressed between the formal leader, teacher leaders, technology personnel, and teachers. For instance, collaborative and horizontally distributed leadership approaches fostered the meaningful integration of technology in one school serving a historically disadvantaged student population (Bingham, 2021), and Tsakeni et al. (2023) illustrated how distributed leadership can enhance opportunities in secondary science and mathematics. Teacher-level evidence further shows that peer, expert, and leader support can continue to foster higher-quality technology integration by building teachers' motivation and persistence (Chiu, 2022).

Despite these advances, the literature remains fragmented. Research on leadership usually investigates digital transformation; research on technology adoption looks at teachers; research on technology integration looks at student engagement in the classroom; and research aimed at equity focuses on student participation, responsivity, and the opportunity to learn. How distributed leadership practices, digital learning support, teachers' practice, and equity-oriented practices in science teaching and learning intersect in teachers' daily lives, especially regarding students who are underrepresented, remains largely unknown. The fragmentation results in a lack of qualitative understanding of how leadership actions at the school level are realized and experienced in relation to digital science practices and learning opportunities at the classroom level. Filling this gap is important because secondary science teachers sit at the interface between leadership decisions and students' day-to-day learning. Their views can serve as a lens through which we understand the outcomes of organizational support for teacher capacity, instructional practice, and equitable digital participation, whether successful or unsuccessful. This research contributes to the literature by synthesizing the concepts of distributed leadership, digital science-learning support, teacher enactment of the program, equity of learning experiences, and perceptions of science-learning outcomes into a single multi-site qualitative study in Lynchburg, VA.

Accordingly, the study aims to explore secondary science teachers' perspectives and experiences regarding how school leadership strategies support the integration of digital learning technologies and promote equitable science-learning opportunities and perceived learning outcomes among underrepresented students. The study provides an integrated, context-sensitive understanding of how leadership practice becomes science instructional support in digital environments and, in turn, influences science learning for equity. Implications for school leadership, teacher learning and development, and the design of more inclusive science learning environments in the digital era in secondary science education are also provided.

2 Literature Review

Distributed leadership provides a useful theoretical context for understanding the organization of support for scientific learning with digital technologies in schools. This vision moves away from a focus on principals as leaders and embraces leadership as a distributed practice that occurs within the relationships among principals, teacher leaders, specialists, and teachers. Empirical research is linked to teacher agency, autonomy, teacher professional partnerships and innovative action under the context of distributed leadership (Hilal et al., 2022; Lin, 2022). Distributed leadership is also associated with better-quality teaching and learning experiences across schools with varying socioeconomic statuses (Tsakeni et al., 2023) in science and mathematics settings. The implications of these findings are important since technology integration is not the work of any one teacher, but requires organizational and pedagogical coordination.

School-level support is continually reflected in the leadership literature as a factor influencing digital integration. Adewale (2025) conducted a literature search and found that teachers' technology acceptance and use in secondary schools were enhanced through repeated strategies by the secondary-school leaders. In a similar study, Yang et al. (2025) found that clear vision, resource allocation, modelling technologies, teacher development, teacher self-efficacy, pedagogical beliefs, and collaborative cultures are factors that affect the depth and sustainability of ICT integration. Teachers' motivation and persistence in integrating higher-quality technology have been enhanced by partner support from peers, leaders, and experts, as shown by Chiu (2022). Capacity building, instructional supervision, strategic technology integration, collaboration, and continuous learning were also among the digital leadership practices identified by Danganan and Gamboa (2025).

These findings do not mean that leadership support automatically produces meaningful classroom practice. There is a gap in implementation revealed by science-specific research. Altan et al. (2025) reported that when teachers were mentored, they incorporated some aspects of technology into their design-based STEM activities, but often used it as an addition to the teaching process rather than as part of the design process. This is important because the quality of technology integration was more strongly correlated with student behavioral engagement and digital competencies than any measure of usage frequency (Consoli et al., 2024). Thus, leadership is not just a means of improving technology use, but can influence the pathway from technology use to pedagogically useful technology use.

The equity literature adds further complexity. Though equitable secondary science teaching must be responsive to students' identities, struggles, relationships, and ideas, it must also increase historically marginalised students' opportunities to engage in disciplinary learning, according to Kang (2021). There is also a need to consider equity beyond access to knowledge to transformative participation and attention to structural inequities, as Rüschenpöhler (2024) argues. In the digital realm, Nguyen (2025) records inequalities in access to devices, internet connectivity and stability, prior digital-leaning experience, and technological skills among those for whom learning online is not a routine part of everyday life. Similarly, emerging technologies can support minority students' engagement and participation in STEM, while technological, pedagogical, and cultural barriers remain obstacles to inclusive implementation (Salas-Pilco et al., 2022). The issues of leadership, teacher enactment, access to digital resources, and equity are therefore linked issues.

A conceptual link can be drawn between these streams: distributed leadership can design and shape the professional and strategic support provided to digital science education; distributed leadership can design and shape how teachers use technology; distributed leadership can shape the equitable learning opportunities and perceived science-learning outcomes of teachers' technology-based enactment. However, the literature is still disjointed. Leadership studies often address technology adoption and/or teacher capacity; technology studies tend to focus on engagement and/or achievement; and equity studies tend to focus on access and/or participation, without connecting that concern to the question of leadership practice. Much of it is also cross-sectional, survey, or is conducted outside the U.S.

Given the qualitative and exploratory nature of the present study, the use of formal hypotheses is not appropriate. Instead, there are sensitizing relationships in the literature that lead us to ask questions but do not dictate the answers. The conceptual, methodological, contextual, and disciplinary gap is the limited research that incorporates distributed leadership, digital science teaching, teacher experience, equity, and perceived outcomes in a multi-site qualitative study. This is the gap the present study attempts to fill by examining how secondary science teachers, in Lynchburg, Virginia, experience digital integration supported by their leaders and how that experience impacts underrepresented students. The resulting relationships are formulated into a modified conceptual model presented in the next subsection.

2.1 Conceptual framework

As shown in Figure 1, the conceptual framework reflects distributed leadership alongside equity-focused principles of Culturally Responsive School Leadership. It starts with distributed leadership practices, continues with leadership strategies for digital science learning, includes some teachers' experiences and perceptions of digital science integration, addresses equal access to digital learning for underrepresented students, and concludes with teachers' perceptions of science learning outcomes. These domains are the sequential areas of inquiry in the study, but they are not causal relationships. The framework thus serves as a guide for the questions asked during the focus groups, supports thematic analysis across the five secondary schools, and provides interpretive scaffolding for understanding leadership practices in relation to digital science learning and educational equity.

3 Research Methodology

3.1 Research Design and Interview Protocol

The study employs a multi-site qualitative descriptive design, using semi-structured focus group

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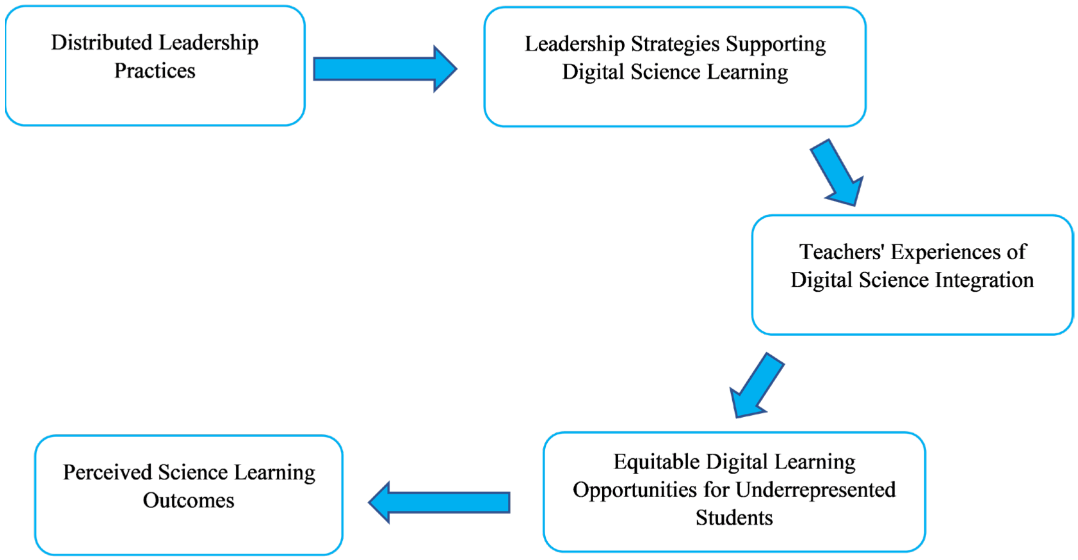

Figure 1. Conceptual Framework

interviews to explore secondary science teachers' perspectives and experiences with leadership strategies that support digital learning technologies, equitable learning opportunities, and perceived science learning outcomes among underrepresented students. The qualitative design is suitable, as it aims to understand how leadership practices are perceived and implemented in secondary science classrooms, rather than to test preconceived causal relationships. The semi-structured interview protocol is designed to relate to the study's objectives and conceptual framework directly and to cover five related domains of study of distributed leadership practices, leadership strategies to facilitate digital science learning, teachers' experiences of integrating digital technology into science instruction, providing equitable digital learning experiences for underrepresented students, and perceived science learning outcomes. The protocol includes open-ended questions to allow participants to share their experiences, practices, enabling factors, barriers, equity considerations, and learning implications as they see them. To ensure consistency and ease of comparison across the five focus groups, the same set of core questions is asked, but the semi-structured interview format allows the moderator to clarify and follow up on relevant experiences and emerging issues. Focus groups take place in different school contexts separately and typically last about 60-75 minutes, allowing participants to build on, agree with, and compare experiences shared by other participants who work in the same school context.

3.2 Participants and Data Collection

The study samples 20 secondary science teachers from the five public secondary schools in Lynchburg, Virginia (three middle and two high schools). Participating schools are designated as School A, School B, School C, School D, and School E to maintain anonymity; school names and potentially identifying school characteristics are not included in the manuscript or analytic records. The number of science teachers is selected using criterion-based purposive sampling, with four teachers per school. Participants currently teach science, are experienced in using digital learning technologies in science teaching, have experience in science teaching to students who are underrepresented or educationally disadvantaged, and have enough knowledge about leadership practices in their school(s) to offer accounts with information. Of the 20 participants, 12 teach at the middle-school level and eight at the high-school level. The range of teaching experience is 2 to 26 years, with an average of 11.5 years, offering insights from those in the relatively early years as well as those with extensive experience. 12 participants have a Master's degree, 7 have a Bachelor's degree, and 1 has an Education Specialist degree. Meaningful differences are identified in self-reported confidence (4–9 out of 10) with digital technologies, with an overall mean score of 6.4. Presenters share their experiences of teaching in integrated science, life science, physical science, Earth and environmental science, biology, chemistry, physics, and other STEM contexts. Data were gathered through five semi-structured focus group interviews, one of which included the four participating teachers from each site. Separate groupings by school allow the institutional context to be maintained and help discuss commonalities and differences across schools in leadership, technology integration, equity, and science learning. Participants are informed about the purpose of the study, voluntary participation, confidentiality, recording procedures and rights of withdrawal prior to participation. When mutually agreed, audio recordings are made of the conversation and later typed out exactly as heard. Participants are assigned pseudonymised identifiers based on a combination of school and teacher codes (e.g., A-T1; A-T2; B-T1), and potentially identifying information is redacted from transcripts, quotations, analytic materials, and reporting following data collection.

3.3 Data Analysis Procedure

Transcripts from the focus groups are analyzed using reflexive thematic analysis as a combined method that is complementary to both deductive and inductive approaches. The first step in the analysis involves re-reading the transcripts and the context analytic notes to become familiar with the participants' accounts and the contextual characteristics of each focus group. This process of coding meaningful chunks of text is systematic and first involves coding leadership practices, digital learning support, teachers' experiences of technology integration and related opportunities, barriers, and outcomes for science learning, as well as perceived science learning outcomes. The conceptual framework is not a template for coding but a set of sensitizing domains that allows the emergence of unexpected experiences, tensions, and meanings inductively from the dataset while keeping the analysis conceptually informed. Recurrent discourse framing and repeated formulations are handled with care during coding, with care taken not to overstate the importance of a theme based on repetition and the presence of similar words; emphasis is placed on conceptual meaning, cross-participant convergence, contrasting accounts, and contextual variation. Coded extracts are used to develop candidate themes, which are then evaluated against the remainder of the data and the overall themes to ensure internal coherence, conceptual distinctiveness, and relevance to the overall research questions before themes are refined, defined, and named. The analytical process is conducted first at the school level, maintaining the same institutional context that each focus group operated within, and then, cross-site analysis to highlight converging patterns, contrasting experiences, differences between the five schools, and differences between the two school types (middle versus high schools). Reflexive analytic memos and systematic records of coding, interpretive decisions, and theme development are kept to enhance transparency and dependability. Final themes are explained within the scope of the research goals and conceptual structure, and one or more representative participant quotations are cited to demonstrate that the final themes have an empirical basis and remain faithful to the teachers' accounts in context.

4 Results

Five interrelated themes emerged from a reflexive thematic analysis of the five school-specific semi-structured focus group interviews: distributed leadership as a professional influence, leadership support for digital science learning, technology as an amplifier of scientific inquiry, equity by design, and perceived science learning outcomes. The participants synthesized the conceptual framework as sensitizing domains in the analysis. However, they developed deeper meanings, contrasted experiences, and contextual variations within the analysis across Schools A–E, to position effective digital science learning as the confluence of leadership support, teacher professional judgment, purposeful integration of technology, and equitable opportunities for students to participate.

4.1 Distributed Leadership as Professional Influence

Participants differentiated between administrative "authority" and "leadership" that had an actual impact on the teaching of digital science. Teachers identified key players for implementing digital programs into class practice, such as members of PLCs, department leaders, trusted teachers, and technology staff. Distributed leadership was most positively felt when teachers had earlier influence on decisions before implementation, tested technologies, and provided feedback and adapted practice based on classroom evidence.

The consultations show an important difference between consultation and consequential participation. The opportunity to provide feedback was not considered true distributed leadership, since most major decisions had already been made. Participation was significant when the decisions to select, implement, or change technology were influenced by professional knowledge.

There were variations between schools. In general, School A showed more structured involvement in PLC and pilot-

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Table 1. Representative Participant Accounts of Distributed Leadership

Participant	School	Transcript
A-T4	School A	"Teacher input is usually gathered through weekly PLC discussion and small pilots before a tool is used more widely."
B-T3	School B	"Many ideas originate with teachers, and pilot lessons are often shared during planning meetings."
C-T3	School C	"Technology expectations are more centrally directed, with the PLC lead and a few experienced teachers advocating for workable classroom adaptations."
E-T2	School E	"Teachers are increasingly asked for feedback, especially after implementation begins. Consultation often follows selection rather than shaping it."

based decision-making, while School B showed more teacher-generated pilot-based decision-making. In School C, it was experienced teachers and PLC leaders who were trying to break down the expectations into viable classroom practices, and in this school, the expectations were more central. School D was more department-based, with science course teams providing evidence from technology trials, and School E had a centralised decision-making process with more teacher engagement, but at a later point in time than in the other schools. Across all sites, the key conditions linked to meaningful distributed leadership were professional voice, opportunities for experimentation, and protected collaborative time.

4.2 Leadership Support for Digital Science Learning

The second theme concerns the type of organizational support teachers felt was needed to make digital science teaching effective. Leadership support was always seen as more than simply buying devices or applications. Pedagogical purpose, sustainable infrastructure, responsive technical assistance, science-specific professional learning and adequate planning time were key elements of effective support.

Table 2. Representative Participant Accounts of Leadership Support

Participant	School	Transcript
A-T1	School A	"Content-specific modeling increases my confidence; a one-time whole-staff tutorial usually tells me where to click but not how to teach the science better."
B-T1	School B	"A stable, reviewed set of tools helps when privacy, accessibility, login, and compatibility questions are settled before teachers build a unit around an app."
C-T2	School C	"A clear message that technology should deepen inquiry, not simply increase screen time, helps us decide when a tool belongs in a lesson."
E-T2	School E	"Integration is easier when common planning is protected long enough to test a lesson, compare student work, and revise it."

The lack of intentional integration and greater technology use was consistent across participation. Leadership expectations were deemed to be helpful when they provided background to support a view that digital technologies are useful and when they provided support for the use of digital tools to support inquiry, visualization, analysis of evidence or feedback and not just as an extension of screen time. This teaching model helped to assess various technologies in terms of their role in science education. It was equally crucial that the operation would be reliable. Well planned science lessons were disrupted due to problems with the device, limited website access, log in problems, software compatibility and delayed technical support. Therefore, responsiveness to platforms and troubleshooting was regarded more as an educational support than just a technical service.

Teachers also emphasized that generic training was inadequate to support the use in disciplinary situations. They valued professional learning that was focused on examples of how specific technology could assist them in supporting students in their scientific models, lab work, inquiry, data analysis, and in providing access to the science classroom. Protected planning time was also very significant as teachers required time to pilot materials, develop options, review learner feedback, and adjust lesson plans. Digital leadership, however, proved to be more of a system that spread throughout schools, encompassing pedagogical direction, technical reliability, the professional, and time.

4.3 Technology as an Amplifier of Scientific Inquiry

The third theme emphasizes the collective perspective of teachers that, in the context of science, digital technology should enhance rather than supplant scientific inquiry. It seemed that most participants started with the scientific question or learning expectation and chose technology only when it contributed to observation, modeling, manipulation, evidence analysis, explanation, or feedback.

Table 3. Representative Participant Accounts of Digital Science Integration

Participant	School	Transcript
A-T3	School A	"The strongest sequence is usually digital-to-physical-to-digital: preview with a model, conduct a hands-on investigation, then analyze and explain the evidence in a shared space."
B-T3	School B	"I often use simulations to make an invisible or fast process visible, then ask students to predict, manipulate variables, and explain what the model leaves out."
C-T3	School C	"Students collect or examine data digitally, graph patterns, compare claims, and return to the evidence when their first explanation does not fit."
D-T2	School D	"I often use molecular modeling to make an invisible or fast process visible, then ask students to predict, manipulate variables, and explain what the model leaves out."

With all the focus groups, simulations, virtual microscopes, virtual labs, molecular models, sensors, and graphing tools used, students were able to interact with phenomena that would otherwise be challenging to observe due to scale, velocity, abstraction, safety, and resource constraints. However, digital visualization was not considered as "learning itself" by the participants. Students should have been able to make predictions, manipulate variables, interpret patterns, make relevant links between representations and evidence and understand the limitations of digital models.

One particular sequence proposed by the participants was digital – physical – digital. The digital representations were used to introduce a phenomenon or to facilitate prediction; the hands-on investigation led to observations and evidence; and the digital environments facilitated organization, graphing, comparison, and explanation. This pattern made technology a supplement to (not a substitute for) physical science experiences. Evidence-based reasoning was also noted as a major emphasis of teachers. Digital tools whose use enabled students to revisit evidence, re-evaluate original assertions, and modify explanations proved most useful. Technology–pedagogy fit, in turn, was perceived as the instructional value of the digital resource, meaning that the value of using technology depended on what the technology enabled students to do scientifically.

Table 4. Representative Participant Accounts of Equitable Digital Learning

Participant	School	Transcript
A-T4	School A	"Captioning, text-to-speech, enlarged models, replay, and chunked directions can make the same science idea more reachable without changing the learning goal."
B-T2	School B	"Some tools work visually but do not work well with captions, keyboard navigation, text-to-speech, or the processing time written into a student's plan. Retrofitting after launch costs the student learning time."
C-T3	School C	"Students with absences, jobs, caregiving duties, or interrupted schedules can miss the sequence that makes a digital investigation understandable; a login alone does not restore the discussion and support."
D-T4	School D	"A district device does not equal dependable access at home. Some students have weak broadband, shared bandwidth, or no quiet workspace."

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4.4 Equity by Design

The fourth theme concerns the conditions necessary for digital learning to be an equal opportunity for underrepresented students. Participants regularly expressed the view that equal access to devices did not mean equal participation with the devices. They highlighted issues with device reliability, connectivity, accessibility, language requirements, participation, and personal circumstances.

Participants identified nominal access with reliable access. Having a device provided by the school did not eliminate problems when equipment broke, accessories were unavailable, the Internet connection was poor, or the home learning environment was not conducive. Likewise, the + button was most helpful when it was part of the lesson from the beginning.

The teachers also mentioned language as a potential barrier to participation. Often, directions can be very complex, and scientific terminology may be used to describe concepts in ways unfamiliar to multilingual learners, making otherwise sophisticated platforms difficult to use. A range of response types, including written, recorded, annotated, and privately submitted responses, was found to help establish further opportunities for classroom use. There was a broader understanding of access. Participants shared examples of when a student might not be able to participate not only in the content but also in questioning, peer interaction, discussions, and the scaffolding their teachers provide during a digital investigation due to absences, work, caregiving, and/or disrupted schedules. With an extension of access to the platform, there was no re-creation of the original learning experience.

In schools, teachers discussed using loan devices, accommodating flexible deadlines, making formats more accessible, providing offline options, and offering school-based completion opportunities. However, their narratives tended to favor a more proactive approach to technology implementation, with accessibility, language, connectivity, and alternative ways of participation taken into consideration prior to implementation. Equity, then, was seen not so much as a problem of remedy in the wake of exclusion as a problem of preventing exclusion, by designing instruction and organization to keep the problem at bay.

4.5 Perceived Science-Learning Outcomes

The fifth theme reflects teachers' perceptions of student learning when digital technologies were used effectively. There were perceived benefits in scientific reasoning, conceptual explanation, formative feedback, engagement, persistence, confidence, and participation. Teachers, however, were concerned that they were not giving evidence-based causal evidence for the influence of technology on improved achievement.

Table 5. Representative Participant Accounts of Perceived Science-Learning Outcomes

Participant	School	Transcript
A-T2	School A	"Students improve at reading graphs and defending a claim when the data are visible, sortable, and shared; they can point to a pattern rather than guess from memory."
B-T2	School B	"Students are more likely to explain a mechanism rather than repeat a definition when they can connect an animation or model to evidence from a lab."
C-T1	School C	"I hear from students who rarely volunteer aloud because they can first respond privately, annotate a model, or prepare an audio or written explanation."
D-T4	School D	"Immediate checks expose misconceptions early enough for me to regroup students and for them to revise before the misunderstanding becomes part of the final lab explanation."

This was seen especially when participants described their students reading graphs, recognizing patterns, linking models to evidence from the lab, and creating explanations based on observable evidence, not just memory. Digital tools were also of particular interest, as a resource to facilitate the formative nature of learning. Responses may be immediate and show some misunderstanding as teaching is still in progress, giving time to clear up what is happening or resetting the class before these misconceptions become part of the finished product. Other digital ways of presenting answers assisted with making students thinking visible for those who did not engage in whole class discussion as much.

Participants also indicated increased engagement and persistence in tasks that were interactive and focused on a scientific question. But no such benefit was not believed to be due to the interactions were possible. Consistently, teachers linked perceived outcomes to task design, instructional support, availability to students, and the purpose of technology use in the lesson. The findings are therefore subjective, and draw on teachers' own views of how effective their support for science learning is likely to be, rather than actual results for achievement.

4.6 Integrative Findings

The outcomes presented in the five themes are connected in a cascade of relationships, distributed professional influence to leadership support, leadership support to teachers' enactment of digital science content, teachers' enactment of digital science content to digital science-learning opportunities, and digital science-learning opportunities to student outcomes. The cross-site variation suggests that these processes are perceived differently depending on the teacher's role in decision-making, science-specific professional support, infrastructure reliability, and protected collaborative time. Together, they highlighted leadership, pedagogy, technology, and equity alignment as essential elements in creating effective digital science learning, distinct from the provision of technology.

4. Discussion

The present study explored how secondary science teachers experience leadership strategies supporting digital learning technologies and equitable science-learning opportunities for underrepresented students. The results from five school-specific focus groups reveal that the supply and availability of digital technology are less important than how it is organised and used in pedagogical practice to enable meaningful digital science learning. The findings that emerged and were linked to each other were as follows: Consequential distributed leadership, integrated leadership support, inquiry-oriented digital integration, proactive equity design, and perceived science-learning outcomes.

Teacher participation was most positively experienced when this resulted in teacher influence. Participants differentiated between being genuinely involved in both piloting and evaluation, changing course due to digital initiatives, and simply following along in matters that have already been decided. This is in line with Bingham (2021) and Tsakeni et al. (2023) on collaborative and horizontally distributed leadership and distributed leadership in science and mathematics environments, respectively. The present study builds on this literature by demonstrating that involvement is not enough without teachers' opportunities to design implementation, time, and discretion.

Support in the provision of technology did not stop there either. Teachers identified the following features as key factors in successful teaching and learning: Direction of instruction, reliable infrastructure, responsive technical assistance, science-specific professional learning, and protected planning time. The findings corroborate those of Yang et al. (2025), who found that vision, resources, professional development, teacher capacity, and collaborative culture are crucial to sustainable technology integration, and those of Chiu (2022), who highlight leader, expert, and peer support. The results presented here also suggest that disciplinary specificity is important and that timeliness is crucial: training in one discipline can be effective for understanding its technological aspects, but not necessarily for teaching science. In addition, providing technical support late, after a lesson has already begun, has less effect.

Another contribution concerns technology–pedagogy fit. The participants talked about the process of producing evidence through a digital–physical–digital sequence, in which digital representations helped predict, hands-on investigation provided evidence, and digital tools then helped analyze, visualize, and explain. This supports Consoli et al. (2024), who emphasize quality over quantity in technology integration. The use of technology is not intended to supplant hands-on science and technology, but rather to enhance scientific inquiry.

This equity perspective on the digital divide adds a new dimension to existing thinking on it. Participants saw device provision as both a means of achieving meaningful access and an element of it. In general, students could derive benefits from digital science learning, depending on connectivity, accessibility, language demands, participation formats, attendance, home responsibilities, and access to interaction with teachers and peers. The results align with the work of Nguyen (2025) and Kang (2021) rather than merely having technology. The findings are similar to those reported by Nguyen (2025) and Kang (2021), emphasizing continuity of access to the full learning process rather than mere access to technology.

From a theoretical perspective, the findings contribute to a revisiting of the conceptual framework: the concepts of distributed leadership, leadership support, teacher enactment, equity, and perceived learning outcomes are

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co-constitutive enabling factors rather than a linear causal chain. One surprising discovery was teachers' negative attitude toward technological determinism. Participants did not necessarily see an association between greater technology use and higher-quality learning, and were cautious about directly linking achievement to technology use. It promotes the interpretation of learning and equity stewardship in leadership by evaluating digital learning programs based on pedagogy, reach, inclusion, and learning opportunities rather than adoption and technology visibility.

From a practical perspective, findings support previous discussions of teachers' engagement at the start of the process of selecting and adopting a technology, science-specific coaching, protected coaching time, rapid technical assistance, and accessibility and language reviews prior to adoption. The study provides a multi-site, qualitative account that combines leadership, digital science pedagogy and equity. The following limitations need to be considered: purposive sampling of 20 teachers from a single city; self-reported perceptions; lack of direct measures of achievement and language, or classroom observations, which may have been influenced by the need to fit in with colleagues within the focus group. Future research should explore a broader context, involve students and school leaders, and draw on broader longitudinal and mixed-methods evidence. In summary, the successful implementation of a digital transformation in Science education requires a realignment of leadership influence, disciplinary pedagogy, scientific technology support, and equity in students' learning opportunities.

5 Conclusion

This study explored secondary science teachers' experiences with leadership strategies that promote the use of digital learning technologies and equitable opportunities for underrepresented students to learn science. The results reveal that digital science education is rooted not only in the availability of technology but also in professional influence, pedagogical guidance, reliable infrastructure, science-specific support, conscious integration, and a proactive focus on accessibility and participation.

A sense of distributed leadership was felt most when teachers could have an impact on decision-making, tool piloting, and the provision of classroom evidence. Coordination of technical and instructional conditions was most likely to gain support from the leadership at different levels. Teachers' acceptance of technology as an aid to scientific inquiry was that it amplified the investigation of scientific phenomena and the use of evidence in reasoning. Equity became a design concern that needed to be addressed with reliable access, language and accessibility support and flexible participation. Participants felt that the students were engaged, reasoning, receiving feedback, participating, and learning conceptually, but did not attribute these to technology.

The study adds to the literature by bringing together three key themes: distributed leadership, digital science enactment, and equity in a single multi-site qualitative study. It also helps advance the interpretive concept of learning equity stewardship, which focuses on making high-quality, accessible learning opportunities available to everyone, rather than on learning opportunities in the context of technology. Meaningfully, the results highlight teacher engagement, allow teachers to plan and reflect on science in a protected time, offer professional development in science, provide responsive technical support, and review accessibility prior to adoption. Some limitations are: a small purposive sample, a single city, teacher perceptions, and a lack of direct measures of achievement. While the findings and implications hold promise for the future, further research should be conducted across more diverse contexts and in mixed-methods designs. Finally, the key ingredients for equity in digital transformation are leadership, pedagogy, technology and access, all centered on substantial science learning.

Author Responsibility

The author is the sole listed author and accepts full responsibility for the integrity, accuracy, interpretation, and final content of the manuscript.

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Conflict of Interest

The author declares no conflict of interest.

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Data Availability Statement

The data supporting the findings of this study are available from the author upon reasonable request, subject to applicable ethical and confidentiality requirements.

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