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Weather-driven school closures and science instruction: Secondary teachers' perspectives on short-term emergency remote teaching

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Abstract

While emergency remote teaching (ERT) during the COVID-19 pandemic has been extensively studied, the distinct pedagogical challenges posed by short-term, weather-related school closures—an increasingly frequent consequence of climate change—remain largely unexplored, particularly in science education. This exploratory qualitative study examined the perspectives of eleven Saudi secondary science teachers on ERT during weather-related school closures, addressing four dimensions: pedagogical adaptations, student learning and performance, challenges, and lessons for future practice. Data from semi-structured interviews were analyzed using hybrid thematic analysis, interpreted through the technological pedagogical content knowledge (TPACK) framework, the community of inquiry (CoI) model, and constructivist learning theory. The findings revealed that teachers primarily transferred familiar instructional strategies to the online environment while selectively integrating digital tools; however, they encountered significant difficulties replicating hands-on, inquiry-based science activities and maintaining student engagement. While teachers perceived that core curriculum objectives were largely achieved, they reported reduced depth of learning, assessment authenticity concerns, and widening performance gaps between digitally prepared and less-prepared students. Key challenges included technical barriers, increased workload, and equity gaps in home learning environments. Unlike pandemic-related ERT, which allowed gradual adaptation over months, weather-related closures are sudden and unpredictable, creating distinct demands that existing preparedness frameworks have not adequately addressed. The study contributes to the literature by extending TPACK, CoI, and constructivist frameworks to weather-related emergency contexts, and offers evidence-based implications for science teachers, policymakers, and teacher educators seeking to build more resilient science education systems.

Keywords: emergency remote teaching, weather-related school closures, science education, science teachers

INTRODUCTION

Background

The prevalence and intensity of weather-related crises have significantly interrupted educational continuity for millions of learners worldwide, disrupting education for 242 million students in 85 countries in 2024 alone (UNICEF USA, 2024). Such interruptions can severely undermine learning: research shows that for upper-elementary and middle school students, each week of missed instruction can lead to two or more weeks of lost academic growth.

A common solution has been to convert weather closures into online instructional days. Yet the evidence is mixed: while remote learning offers continuity, many districts report uneven effectiveness, especially for younger learners and marginalized students (Tzimiris et al., 2023). In contrast to well-planned online learning, such transitions should be conceptualized as emergency remote teaching (ERT).

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Contribution to the literature

- This study documents Saudi secondary science teachers' experiences of short-term, weather-related emergency remote teaching, addressing a context less researched than extended pandemic closures.
- Teachers' accounts underscore the importance of preparedness cultivated before disruptions and identify persistent challenges in inquiry, interaction, and assessment authenticity.
- The findings provide context-specific insights that may inform the development of science-specific resources, equitable access, and sustained preparation for future disruptions.

While the COVID-19 pandemic has been extensively examined through the lens of ERT research, the overwhelming majority of this literature addresses long-duration closures that unfolded over months, allowing teachers and institutions time to adapt, access professional development (PD), and refine their approaches iteratively. Weather-related school closures present a fundamentally different challenge: they are sudden, unpredictable, typically short-term, and recurring.

Moreover, unlike pandemic closures, weather-related ERT in science education carries a specific burden— the loss of laboratory work, hands-on inquiry, and experimental learning that are central to science pedagogy and difficult to replicate online under any circumstances. Despite the increasing frequency of weather-driven school disruptions worldwide, this distinct form of ERT has received remarkably little empirical attention.

Online science education faces significant challenges. The main obstacle is the lack of physical, embodied experiences in virtual settings (Gray, 2025; Saldívar-Almorejo et al., 2024). Research also shows that virtual labs reduce behavioral and cognitive engagement (Post et al., 2019) and fail to provide the procedural and sensorimotor skills developed through real-world experimentation (Van den Beemt et al., 2023).

In Saudi Arabia, where the government has invested heavily in digital platforms such as Madrasati ("My School"), weather-induced closures have made ERT a practical necessity. Yet despite robust infrastructure, readiness remains uneven. Importantly, almost all published Saudi research has focused on the COVID-19 pandemic context, while few studies have examined short-term, weather-driven closures in K-12 science education—despite their increasing occurrence. For instance, severe weather such as storms recently forced schools across multiple Saudi regions to switch to remote learning (Farag, 2024), yet the pedagogical implications of such disruptions remain underexplored. Addressing this gap, the present study analyzes Saudi science teachers' perspectives on ERT during weather-related closures.

Literature Review

Emergency remote teaching

Remote teaching broadly refers to educational arrangements in which teachers and students are physically separated and interact via technology. In crisis contexts (e.g., natural disasters, conflict, and pandemics), distance education serves as a vital mechanism for maintaining instructional continuity. The Inter-Agency Network for Education in Emergencies (2022) emphasizes that distance education is an integral component of education in emergencies, highlighting inclusion and equity as foundational principles for all education modalities.

According to Hodges et al. (2020), ERT refers to a short-term adjustment of teaching methods to a remote format necessitated by crises, with educators typically depending on readily accessible tools—video conferencing, mobile devices, radio, or printed materials—rather than sophisticated e-learning systems. Macias et al. (2022b) found that ERT often involved simplified pacing and selective content coverage, reinforcing the improvisational nature of this approach.

In the years following the COVID-19 pandemic, the concept of ERT has evolved from a reactive instructional response into a framework for educational resilience and preparedness. Bozkurt and Sharma (2020) noted that universities and schools around the world relied on ERT as an urgent response strategy to ensure that instruction could continue despite the disruption, cautioning against equating such emergency practices with well-designed online education. UNESCO (2025) reports that it has implemented around 320 education in emergency initiatives across 133 countries. Bond (2020) emphasizes that engagement and achievement in online learning are highly dependent on instructional design and support context.

Emergency remote teaching in science education

Teaching science subjects at a distance poses special challenges due to hands-on experiments and investigations. For example, Macias et al. (2022b) found K-8 science instruction fell dramatically during COVID-19, prompting educators to increasingly turn to virtual laboratories and simulations as substitutes for in-person experiments.

Ray and Srivastava (2020) emphasized that online classes and digital resources can serve as effective alternatives to in-person learning. Similarly, Sung et al. (2021) found that a non-centralized remote lab system (significantly enhanced student engagement in virtual chemistry courses. Other strategies include at-home experiment kits and teacher-recorded demonstrations. Assessment methods have also been adapted: teachers employ open-book tasks, video lab reports, and conceptual questioning. This aligns with the technological pedagogical content knowledge (TPACK) framework, which highlights how educators integrate content, pedagogy, and technology in real time to maintain instructional integrity during crises (Mishra & Koehler, 2006).

Student engagement and learning outcomes

ERT can affect learners' motivation, equity of access, and achievement. Engagement often suffers when students are isolated from teachers and peers. Equity issues are especially acute: Golden et al. (2023) observed that distance learning intensified existing digital divides and disproportionately affected marginalized youth. The community of inquiry (CoI) framework also helps explain this gap by analyzing how the absence of teaching presence, cognitive presence, or social presence weakens the learning experience in remote settings (Garrison et al., 2000).

Performance outcomes likewise declined on average. A recent meta-analysis found that the pandemic-related schooling disruption produced an overall learning deficit equivalent to about 0.19 standard deviations on achievement tests (Di Pietro, 2023). Notably, this analysis reported larger learning declines in STEM subjects. Key issues include unequal access (the digital divide) and reduced student engagement, as many learners struggled to self-regulate and remain motivated without in-person support. Nonetheless, where schools provided high-quality digital content and sustained teacher guidance, some students demonstrated greater resilience and adaptability in online learning environments.

Teacher experiences and pedagogical adaptations

Many educators had limited prior preparation for digital pedagogy, with most having to rapidly learn new technologies and design virtual lessons almost overnight (Hodges et al., 2020). Consequently, PD became imperative; in contexts where effective training and institutional support were supplied, educators reported enhanced confidence and digital literacy (Trust & Whalen, 2021). Multiple studies have also found that emergency transitions placed substantial stress on teachers due to high workloads (Adedoyin & Soykan, 2020; Sokal et al., 2020).

In the classroom, teachers employed a range of strategies to sustain engagement and learning. These included more frequent formative checks (quizzes and polls), multimedia resources (videos and simulations), and creative projects that could be completed at home (Rapanta et al., 2021). Science teachers, for example, devised hands-on activities using everyday materials to maintain inquiry-based learning. Indeed, many educators experimented with new delivery modes—synchronous virtual labs, flipped lessons, and online discussion boards, and discovered potential benefits such as increased student autonomy (Rapanta et al., 2021). However, the strain was real: teachers in fully remote or under-resourced contexts often felt overwhelmed managing technology (Pressley, 2021). Students also highlighted challenges in online assessment integrity and proposed alternative evaluation models such as open-ended projects or oral tasks to address cheating concerns (Kebritchi et al., 2017).

Emergency remote teaching in Saudi Arabia

Global education agencies stress the importance of proactive preparation for emergency learning. Studies emphasize that building teacher capacity and institutional readiness for remote instruction can better prepare education systems for future disruptions (Hodges et al., 2020; Trust & Whalen, 2020).

Saudi Arabia has rapidly expanded its ERT infrastructure, particularly following the COVID-19 pandemic, notably through Madrasati—a unified national e-learning platform launched by the Ministry of Education in 2020 that reached approximately 98% of Saudi K-12 students during the 2020-2021 school closures, serving more than six million learners nationwide (World Bank, 2022).

During weather-related closures, the Ministry of Education has continued activating ERT through Madrasati—for instance, in May 2024, when the Riyadh Education Directorate shifted all schools to Madrasati-delivered instruction due to heavy rains (Saudi Press Agency, 2024).

Teacher feedback during and after the pandemic was largely positive: a World Bank (2022) national survey found most teachers believed students' digital literacy and independent learning skills improved under remote instruction. Nonetheless, challenges persisted: younger learners were more vulnerable to disengagement and fatigue. According to the World Bank (2022), approximately half of Saudi students reported that they would have learned more if they could have returned to in-person schooling. Recognizing these challenges, the Ministry of Education has announced plans to explore blended learning models further beyond the pandemic (World Bank, 2022).

Problem Statement

Weather and climate-related emergencies (e.g., heavy rain, storms, and sandstorms) increasingly force Saudi schools to close temporarily, turning in-person science classes into ERT days. Emergency shifts also magnify existing inequities: students without reliable internet or devices face the greatest challenges. Science educators face additional difficulties, as hands-on laboratories and experiments integral to the science learning process are challenging to replicate in a virtual environment. Take-home experiments and virtual simulations can help, but they increase planning time and only partially substitute for in-class inquiry activities. Crucially, existing studies of Saudi remote teaching focus almost exclusively on pandemic closures; weather-driven ERT in K-12 science has been essentially unexamined.

This study therefore addresses an urgent research gap. By examining science teachers' perspectives, experiences, adaptations, and reported outcomes under these conditions, the study aims to identify key barriers—including digital inequities, the loss of hands-on learning, and increased workload—as well as effective coping strategies employed by science teachers.

Purpose of the Study and Research Questions

The purpose of this qualitative study is to investigate how Saudi science teachers experience and respond to a temporary shift to ERT during weather-related school closures. In particular, the study aims to explore the adaptations these teachers make in their science teaching practices, examine their perceptions of student learning outcomes and performance under remote teaching conditions, identify the challenges or barriers they encounter in delivering science education online during such closures, and elicit the lessons or insights they have gained for improving future practice.

In alignment with the study's purpose, one overarching research question (RQ) and several sub-questions were formulated to guide the inquiry.

Main research question: What are Saudi science teachers' perspectives on the temporary shift to ERT during weather-related school closures, particularly regarding its impact on their science teaching practices?

Sub-research questions: To answer the main question in depth, the study addresses the following sub-questions, each targeting a specific facet of the teachers' experience:

RQ1. Pedagogical adaptations: What pedagogical adaptations did science teachers employ to maintain effective science instruction during ERT?

RQ2. Student learning and performance: How do science teachers' perspectives reflect their views on the effectiveness of ERT during weather-related closures in achieving science learning objectives, particularly regarding learning quality and student performance?

RQ3. Challenges: What challenges or barriers did science teachers encounter in delivering science education remotely during the weather-related school closure period?

RQ4. Lessons for future practice: What insights do science teachers report having gained from their experience with ERT, and how do they believe these should inform future practice or policy for managing similar educational disruptions?

Theoretical Framework

To address these RQs, this study draws on three complementary theoretical perspectives that illuminate technology-mediated instruction, teacher knowledge adaptation, and science learning in emergency contexts.

The first guiding framework is the TPACK model, which conceptualizes effective pedagogy as the dynamic convergence of content knowledge (CK), pedagogical knowledge (PK), and technological knowledge (TK) (Mishra & Koehler, 2006). TPACK thus provides a lens for analyzing how teachers combine subject knowledge and pedagogy through technology and how this interaction reshapes inquiry-based science learning during short-term disruptions. Within this study, TPACK informs the design of interview questions and the coding framework to capture teachers' technological, pedagogical, and content integration.

The second theoretical lens is the CoI model (Garrison et al., 2000), which frames effective online learning as the interplay of teaching presence, social presence, and cognitive presence. Teaching presence involves how instructors design, facilitate, and guide learning; social presence reflects how learners build community; and cognitive presence captures the processes of inquiry and meaning-making.

Finally, constructivist learning theory underpins the study's overall interpretation of science education. Constructivism posits that learners actively construct knowledge through discovery and social interaction (Bruner, 1961; Vygotsky, 1978). From this standpoint, the study explores how teachers attempt to preserve active, experimental, and collaborative learning in emergency online contexts.

While TPACK serves as the primary analytical lens, CoI and constructivism provide complementary perspectives for understanding interaction patterns and knowledge construction during weather-related ERT. The three frameworks are related sequentially rather than independently, as illustrated in **Figure 1**. TPACK represents teachers' underlying technological-pedagogical capacity—the readiness to translate CK into effective technology-mediated instruction. This capacity enables teachers to enact the three presences described by the CoI model in the virtual classroom. These enacted presences, in turn, create the conditions under which constructivist learning processes—active exploration,

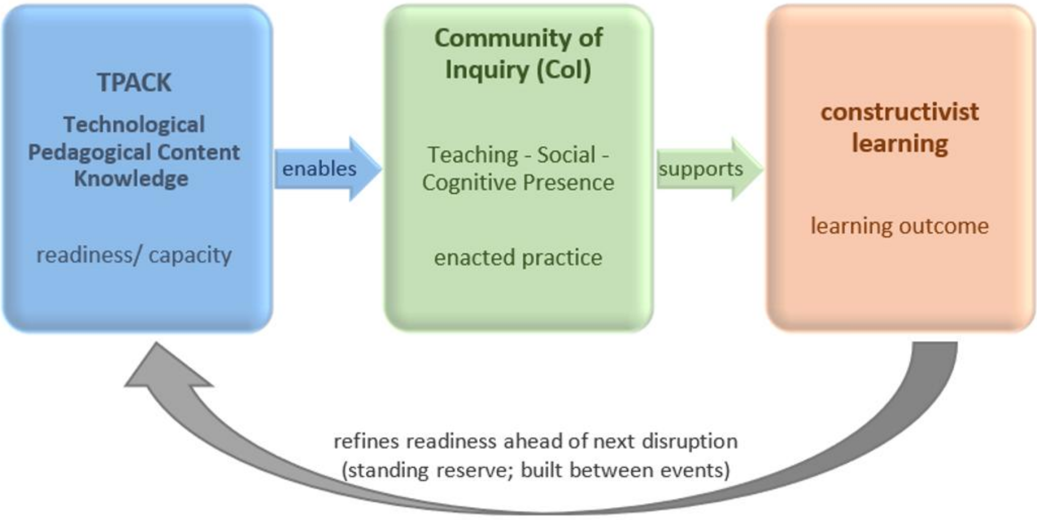

Figure 1. Relationship among the study's theoretical frameworks (the author's own work)

Table 1. Participants' information

Teachers' names (pseudonyms)	Science major	Years of teaching experience	Prior ERT experience	PD on ERT
Teacher A	Chemistry	14	Yes	3
Teacher B	Chemistry	9	Yes	3
Teacher C	Chemistry	12	Yes	5
Teacher D	Physics	15	Yes	3
Teacher E	Physics	7	Yes	4
Teacher F	Physics	9	Yes	3
Teacher G	Physics	12	Yes	5
Teacher H	Biology	10	Yes	3
Teacher I	Biology	7	Yes	4
Teacher J	Biology	9	Yes	4
Teacher K	Biology	11	Yes	3

social meaning-making, and knowledge construction—become possible for students. As discussed further below, the findings of this study also suggest a reciprocal relationship: because weather-related ERT events are brief and recurring rather than sustained, the outcomes of one disruption feed back into and refine TPACK ahead of the next event.

MATERIALS AND METHODS

Research Design and Participants

This study used a qualitative descriptive design to explore teachers' experiences during ERT. Consistent with the exploratory qualitative design and the principle of information power (Malterud et al., 2016), eleven science teachers from secondary schools in the Eastern Region of Saudi Arabia were recruited through purposive sampling. The sample size was deemed appropriate given

(a) the narrow and specific aim of exploring teacher perspectives,

(b) the rich experiential knowledge of participants who had experienced weather-related ERT, and

(c) the use of strong theoretical frameworks to guide analysis.

Variation in teaching experience and science specializations was ensured to capture diverse perspectives. All participants hold a bachelor's degree in science education or a related field. Their teaching experience ranged from 5 to 20 years. All had prior experience with ERT and had attended between three and five PD workshops related to ERT due to a weather-related school shutdown. All taught science subjects—chemistry, biology, or physics (**Table 1**).

The researcher is a Saudi science education academic with prior teaching experience in Saudi secondary schools, which provided both insider familiarity with the cultural and institutional context and an awareness of potential bias. Furthermore, the study was approved by the Institutional Review Board at Imam Abdulrahman Bin Faisal University on October 15, 2025, with approval number IRB-2025-15-053. All participants provided written informed consent, and confidentiality was maintained by replacing identifying details with pseudonyms throughout the data.

Data Collection

The interview protocol began with introductory questions to establish rapport and gather each teacher's general background. The core interview items explored four key thematic areas aligned with the study's sub-RQs:

(a) pedagogical adaptations implemented to sustain science instruction during ERT,

(b) teachers' perceptions of student learning and performance,

(c) challenges and barriers encountered during remote delivery, and

(d) lessons and insights for improving future practice and policy.

All interviews were conducted by the researcher to ensure consistency in data collection procedures. The interviews were conducted in the participants' native language (Arabic) to enable nuanced expression. Each interview lasted approximately 45-60 minutes. All interviews were audio-recorded and then transcribed verbatim in Arabic. Coding and thematic analysis were performed on Arabic transcripts to preserve cultural and linguistic meaning. Selected illustrative quotations were translated into English by the researcher; a bilingual colleague reviewed the translations for accuracy through back-translation.

Data Analysis

Interview transcripts were analyzed using hybrid thematic analysis, combining inductive coding with deductive codes derived from the study's theoretical frameworks (Fereday & Muir-Cochrane, 2006). The researcher first conducted open coding independently to identify significant phrases and ideas related to each RQ. To enhance the reliability of the analysis, a colleague with expertise in qualitative research independently reviewed a subset of transcripts and the initial codes. The researcher and colleague then met to compare, discuss, and refine the codes through iterative dialogue. Any disagreements were resolved by returning to the original data and discussing until consensus was reached. Codes were subsequently grouped into broader themes. A codebook was developed to define each theme and code, with example teacher quotes to ensure clarity and consistency (see **Appendix A**).

Deductive codes were derived directly from the study's three guiding frameworks—TPACK, CoI, and constructivist learning theory—and applied to segments of text describing technology use, presence (teaching, social, cognitive), and student-centered learning processes. Inductive codes were developed independently through open coding to capture patterns not anticipated by these frameworks, including subject-specific constraints (e.g., laboratory-dependent instruction) and workload-related consequences of remote delivery. Where inductive codes overlapped conceptually with a deductive category, the researcher and the independent coder discussed whether to retain the code as a distinct inductive theme or subsume it within the relevant framework-derived category, resolving disagreements by returning to the original transcripts. Codes were then iteratively grouped into broader themes through constant comparison across transcripts, with theme boundaries refined across three rounds of review until each theme was internally coherent and clearly distinguishable from the others. This coding process, together with the finalized codebook (**Appendix A**), provides a transparent record of the analytic process.

Trustworthiness

Several strategies were used to enhance trustworthiness in accordance with Lincoln and Guba's (1985) criteria. *Credibility* was supported through analyst triangulation: an independent qualitative researcher separately coded a subset of the transcripts, and coding discrepancies were resolved through discussion and repeated reference to the original data. *Dependability* was supported through documentation of the coding process and the finalized codebook (**Appendix A**), which records how codes and themes were defined and refined. *Confirmability* was supported through the researcher's explicit acknowledgment of insider positionality and the use of direct participant quotations to demonstrate the connection between the data and the study's interpretations. *Transferability* was supported by providing thick contextual description of participants' backgrounds, teaching contexts, and the study's regional and institutional setting (**Table 1**), enabling readers to assess the applicability of the findings to other contexts. Nevertheless, member checking was not conducted, and the study relied on a single data-collection method—semi-structured interviews—without triangulation across data sources. The implications of these limitations are discussed further in the limitations section.

RESULTS

This section presents the qualitative findings from interviews with eleven science teachers who experienced ERT during weather-related school closures. The results are organized by the study's four sub-research questions, each addressed in a separate subsection. Following each set of findings, an integrated discussion interprets the results. A summary of the themes, codes, and representative quotations derived from the data is presented in the codebook (see **Appendix A**). While the codebook (**Appendix A**) provides a transparent record of the codes and their definitions, **Table 2** synthesizes the resulting themes and codes in relation to the study's three theoretical frameworks—TPACK, the CoI model,

Table 2. Themes, codes, and their relationship to the study's theoretical frameworks

Theme	Code	TPACK dimension	CoI presence	Constructivist link
Pedagogical adaptations	Strategy continuity	TK/PK (baseline)	Teaching	-
	Digital expansion	TPK	Teaching	Active exploration (partial)
	Perceived constraints	TPACK (content-specific)*	Social, cognitive	Experiential learning constrained
	Virtual lab integration	TPACK (content-specific)	Cognitive	Simulated experiential learning
Student learning and performance	Passive participation	TPK (limited)	Social	Barrier to active exploration
	Autonomy gains	TPK (effective)	Cognitive	Self-regulated learning supported
	Teacher digital growth	TK (developing)	Teaching	-
Challenges of online science teaching	Technical barriers	TK (gap)	Teaching	-
	Workload and adaptation	TK/TPACK (compound)	Teaching	-
	Assessment authenticity	TPACK (assessment gap)	Cognitive	Difficulty verifying constructed understanding
	Student readiness and equity	TK (access-related)	Social	Unequal access to exploration opportunities
Support, communication, and future practices	Family involvement	TPK	Social	Extended scaffolding network
	Motivation and flexibility	TPK	Teaching	Scaffolded encouragement
	Student tech training	TK → TPK	Teaching	Scaffolding (Vygotsky, 1978)
	Weekly online practice	TPACK (standing reserve)	Teaching, social, cognitive	Progressive skill-building

Note. *The "perceived constraints" (teachers A, B, and C – chemistry) and "virtual lab integration" (teacher F – physics) codes together reflect the subdiscipline-based pattern discussed before: chemistry teachers consistently described the online format as restrictive, while physics and biology teachers did not

and constructivist learning theory—to support the conceptual synthesis discussed throughout this section.

Sub-Question 1: Pedagogical Adaptations

Teachers described how they adapted pedagogy to ERT. Many transferred familiar in-class strategies, such as brainstorming, concept mapping, structured discussion, and direct instruction with slides, into the online environment with minimal change. For instance, teacher B noted, "I didn't change much, I used the same PowerPoint slides and the same structure as in class." Teachers also leveraged platform features such as Microsoft Teams and Madrasati to approximate classroom activities, including whiteboards, chat, and limited cooperative learning. Several emphasized the utility of the virtual lab for simulating experiments .

At the same time, a subset of teachers introduced incremental innovations, such as flipped learning, short pre-class videos, embedded multimedia, and quick online research tasks to sustain engagement. As teacher G explained, "I uploaded short videos before class; live time focused on discussion and problem-solving." Pacing adjustments were also common, including shorter segments, interleaved comprehension checks, and clearer materials tailored for screen-based delivery.

However, a minority of the participants felt constrained by the remote format. Teacher A noted, "In distance learning, the strategies used are lecture and discussion. I feel restricted in using these strategies… I cannot apply all available strategies because learning is remote." Similarly, teacher B added, "Cooperative learning cannot be applied in distance learning. I use it in person—dividing students into groups or pairs but online it is not feasible." In contrast, other teachers reported no substantive limitations. Teacher H said, "I believe I can apply all strategies; there is no problem." Teacher F described ERT as "efficient and enjoyable for teacher and student," pointing to cooperative learning features in Microsoft Teams and the availability of a virtual lab as effective alternatives to in-person activities.

These contrasting accounts point to a disciplinary pattern rather than idiosyncratic individual variation. All three chemistry teachers in the sample (teachers A, B, and C) described the online format as restrictive, citing the difficulty of transferring cooperative and hands-on strategies to a remote setting. In contrast, no physics or biology teacher reported comparable constraints; several, including teacher F and teacher H, described the transition as unproblematic or even positive, pointing to virtual labs and simulation tools as adequate substitutes for in-person activities. One plausible interpretation is that the degree of pedagogical constraint teachers experienced under ERT was related, at least in part, to the extent to which a subject's core instructional activities depend on physical manipulation of materials. Chemistry instruction—reliant on titrations, reagent handling, and procedural lab technique—may have been harder to approximate virtually than physics or biology content, which lent itself more readily to demonstration, simulation, or discussion-based delivery. This explanation based on subject differences should be viewed as one plausible interpretation rather than a conclusive explanation; other factors not fully captured by this sample, such as individual teaching experience, digital competence, or institutional support, may also have contributed to the observed pattern. This subdiscipline-level distinction has not typically been disaggregated in prior applications of TPACK to ERT contexts, and it suggests that pedagogical readiness for emergency remote science teaching may need to be considered separately by science subdiscipline rather than treated as a uniform construct.

These findings reflect the dynamic integration of technology, pedagogy, and CK central to the TPACK framework (Mishra & Koehler, 2006). Teachers demonstrated varying levels of technological pedagogical knowledge (TPK), with some seamlessly transferring existing practices while others innovated to leverage digital affordances such as flipped learning and virtual laboratories. The predominant strategy of transferring familiar approaches aligns with ERT patterns reported internationally; Hodges et al. (2020) note that teachers under emergency conditions typically prioritize instructional continuity over pedagogical transformation .

Through the lens of the CoI model (Garrison et al., 2000), teachers who maintained questioning, structure, and clear organization sustained teaching presence in the virtual environment. However, the reported constraints on collaborative and hands-on work suggest reduced opportunities for social presence (peer interaction and community building) and cognitive presence (inquiry and knowledge construction). Overall, ERT relies heavily on digital tools and creative pedagogy to sustain practical learning in the absence of physical laboratories. This aligns with Bozkurt and Sharma's (2020) observation that emergency conditions often compromise the interactive dimensions of online learning.

From a constructivist perspective (Bruner, 1961; Vygotsky, 1978), the difficulties teachers reported with cooperative learning and hands-on activities represent significant challenges for science education: active exploration and social interaction, central to knowledge construction, were difficult to replicate fully during sudden weather-related closures. While virtual laboratories provided partial solutions for simulating experiments, they could not entirely replace the direct experiential learning that characterizes effective science instruction.

Sub-Question 2: Student Learning and Performance

The majority of teachers highlighted contrasts in students' engagement. Many reported passive participation, minimal responses, and difficulty monitoring attention. Teacher E noted, "Many students rarely turned on their microphones. It's as if I'm talking to silence." Teacher B said, "Only a few students responded; the rest just logged in." Teachers stressed the loss of visibility: "In face-to-face learning, the student sits across from you, so you can follow up and redirect. In distance learning, you don't see the student; this becomes a barrier" (teacher H). "Some students neglected communication and attention online, unlike the classroom where we immediately notice and intervene" (teacher G).

In parallel, several teachers perceived developmental benefits. Teacher F stated, "Distance learning enhanced my technological skills that I developed myself to adapt." Teacher I said, "For students, online learning increased responsibility; tasks before and during class give them more time, raising the quality of learning." Teachers also emphasized the need to build autonomy: "We should raise awareness among students and families so students rely on themselves to access the lesson, use platforms, and participate independently" (teacher G). Furthermore, two contrasting narratives emerged. On one hand, the sudden shift weakened key elements of effective science learning—particularly engagement, dialogue, and visibility. On the other hand, the shift catalyzed unexpected gains in student autonomy and self-regulation for a subset of learners, suggesting ERT may differentially affect students according to their pre-existing readiness.

Rather than representing contradictory findings, these two patterns likely reflect distinct and coexisting effects of the same structural shift. Passive participation stemmed primarily from the loss of visual and behavioral cues that teachers rely on in person—the ability to see a student's face, notice disengagement, and intervene in real time. This is a loss of immediacy, not necessarily of underlying motivation. Autonomy gains, by contrast, emerged specifically where teachers introduced structured, self-paced tasks—pre-class assignments, independent research activities—that shifted responsibility onto students rather than relying on real-time visibility to sustain engagement. In other words, ERT did not uniformly help or harm student learning; it removed a mode of engagement dependent on teacher visibility while simultaneously creating conditions that, when paired with deliberate task design, could foster self-regulation. The two effects are not in tension—a single class could plausibly exhibit both, with some students disengaging in the absence of visible monitoring while others thrived under the added structure and responsibility. This suggests that student outcomes under weather-related ERT depend less on remote delivery itself than on whether teachers replaced lost visibility with alternative structures for engagement and accountability.

Looking at the CoI model (Garrison et al., 2000), the reported difficulties with passive participation and invisible students indicate diminished social presence—the ability of learners to project themselves and establish personal connections. Teachers' challenges in monitoring attention and providing immediate feedback reflect reduced teaching presence, particularly in facilitation and direct instruction. Furthermore, the constraints on interactive discussion and collaborative sense-making suggest limited cognitive presence, which is essential for scientific inquiry and knowledge construction.

From a constructivist perspective (Bruner, 1961; Vygotsky, 1978), the passive participation reported by teachers—students logging in without engaging—represents a significant barrier to constructivist learning. Science education, in particular, relies on discourse, questioning, and collaborative reasoning to develop scientific understanding; these processes were difficult to sustain when students remained invisible and silent online.

However, some teachers observed developmental benefits. The TPACK framework (Mishra & Koehler, 2006) suggests that effective technology integration can create new opportunities for learning. Teachers who implemented structured digital routines such as pre-class tasks and independent research activities observed increased student responsibility and self-direction. This indicates that when TK is thoughtfully combined with pedagogical and CK, ERT can foster autonomy and metacognitive skills.

Overall, student engagement and learning during weather-related ERT was shaped by multiple factors, including instructional design, home learning environment, and students' readiness for independent learning (Adedoyin & Soykan, 2020; Bond, 2020). The sudden, unpredictable nature of weather-related closures intensified these challenges, as teachers had limited time to design engaging online activities or prepare students for remote learning.

Sub-Question 3: Challenges

Most teachers identified several interrelated challenges that influenced their ability to implement science teaching effectively during ERT. The difficulties they reported were clustered into four main categories: technical barriers, workload and adaptation pressures, assessment validity, and student equity and readiness.

Technical barriers

Teachers consistently emphasized technical problems as a major obstacle to effective ERT. Weak internet connections, platform instability, and students' limited access to suitable devices frequently interrupted lessons. Teacher A explained, "Sometimes the platform would stop or students could not enter the session. This wasted time and broke the flow of the lesson."

Several teachers also highlighted that although their schools used Microsoft Teams through the "Madrasati" system, many students faced limited access to computers at home. As teacher C described, "Some families had only one computer while having several children, which made it difficult for everyone to attend at the same time." However, teacher C further noted that "families solved this problem by using multiple devices such as smartphones and iPads, not just desktop computers." This adaptability helped minimize disruption, yet the inequality in device availability remained a persistent barrier to equitable participation.

Workload, preparation, and adaptation pressure

Several teachers reported an increased workload when converting science lessons to online formats. Preparing digital materials, uploading assignments, and following up with absent students required more time than traditional teaching. Teacher G shared, "Before each lesson, I had to upload materials, check attendance, respond to questions, and post feedback after class. It was much more work than teaching in person." Similarly, teacher K remarked that the constant switching between platforms and messaging channels caused fatigue, saying, "I felt I was working all day preparing, teaching, and replying to messages from students and parents."

Assessment and authenticity challenges

Several teachers voiced major concerns about assessing student performance and verifying academic honesty in the remote setting. Teacher D reflected, "Online it's hard to tell if a student answered independently. They may use search engines or read from the book." Teacher F elaborated, "I cannot be sure whether the answer shows understanding or is copied from somewhere." To counter these problems, teachers shifted toward alternative forms of assessment such as projects, oral questioning, and performance-based tasks. However, these measures were time-consuming and not always feasible for large classes. As teacher B summarized, "I prefer face-to-face assessment because I can observe and ask directly whether the student really understands."

Student readiness, motivation, and equity gaps

Several teachers also raised concerns about student motivation, home learning environments, and equity of access. Some students lacked quiet spaces, reliable internet, or parental support, which hindered their learning. Teacher H explained, "Some students sometimes face problems with internet connection or share one device with siblings. It's hard for them to attend regularly." Others struggled with self-discipline, as teacher C observed, "Students need to be mature to study online; many lost focus or skipped lessons because no one monitored them." These teachers recognized that these disparities directly affected learning outcomes, creating inequities between well-supported and disadvantaged learners.

Although presented separately, these four challenges were not independent; several shared a common root or compounded one another. Technical barriers and equity gaps, for instance, were largely two expressions of the same underlying constraint—unequal access to reliable devices and connectivity—rather than distinct problems; teacher C's account of families redistributing smartphones and tablets illustrates how the same resource scarcity produced both an immediate technical disruption and a longer-term equity concern. Workload pressures, in turn, were partly a downstream consequence of the other three challenges rather than a freestanding source of strain: teachers described additional hours spent troubleshooting technical failures (teacher A), redesigning assessments to address authenticity concerns (teachers B, D, and F), and individually supporting students with unstable access (teacher H). Understood this way, the workload increase reported across the sample functioned less as a separate obstacle than as the aggregate cost of compensating for the other three. This suggests that interventions targeting device access and connectivity directly would likely ease both the equity and workload challenges simultaneously, rather than requiring four separate solutions for what are, at root, two underlying problems.

Overall, the challenges teachers experienced align with the literature emphasizing that ERT demands simultaneous management of pedagogy, technology, and learner readiness (Adedoyin & Soykan, 2020; Bozkurt & Sharma, 2020). The sudden, unpredictable nature of weather-related closures intensified these challenges, as teachers had minimal time to prepare digital materials or troubleshoot technical issues before instruction began.

Within the TPACK framework (Mishra & Koehler, 2006), teachers often found that their TK lagged behind their PK and CK, forcing them to develop digital skills under pressure. This imbalance was particularly evident in science instruction, where teachers struggled to translate hands-on, inquiry-based activities into online formats. The challenge of replicating laboratory experiences online reflects a gap in TPACK—the intersection where technology, pedagogy, and science content must be seamlessly integrated.

As viewed through the CoI model (Garrison et al., 2000), the reported challenges reveal disruptions across all three presences. Teaching presence was compromised by technical barriers and increased workload, which limited teachers' ability to design and facilitate effective online instruction. Social presence suffered from inequitable access, poor connectivity, and students' passive participation, reducing opportunities for meaningful interaction and community building. Cognitive presence—the process of inquiry and knowledge construction central to science learning—was undermined by assessment ambiguity and students' limited engagement with course content.

From a constructivist perspective (Bruner, 1961; Vygotsky, 1978), the challenges reported by teachers represent significant barriers to effective science learning: the technical barriers, equity gaps, and reduced interaction reported by teachers limited students' opportunities for collaborative meaning—making and hands-on discovery—processes essential to science education.

Assessment authenticity emerged as a critical challenge with particular implications for science education. Rapanta et al. (2020) identify assessment as a systemic challenge in online contexts, and teachers in this study echoed this concern. The inability to verify whether students genuinely understood scientific concepts, rather than simply copying answers, undermines the validity of assessment and makes it difficult for teachers to gauge learning progress. While alternative assessments such as projects and oral questioning partially addressed this issue (Kebritchi et al., 2017), they increased teacher workload and were not always feasible for large classes.

The equity concerns raised by teachers are particularly significant. Students without reliable internet, adequate devices, or supportive home environments faced compounded disadvantages during weather-related ERT. This digital divide exacerbates existing educational inequities and poses a serious challenge to ensuring all students achieve science learning objectives (Bozkurt & Sharma, 2020).

Despite these difficulties, teachers demonstrated resilience and adaptability. They drew on communication skills, self-directed learning, and flexibility to sustain instruction amid challenging circumstances. This adaptability reflects a growth in TK that, over time, may strengthen teachers' overall TPACK and better prepare them for future disruptions.

Sub-Question 4: Lessons for Future Practice

Most teachers described multilayered support strategies that they developed during weather-related ERT. They used platform messaging for follow-up and feedback beyond live sessions. Teacher B explained: "I sent notes via Madrasati and replied to messages the next morning." Teachers engaged families to maintain continuity, contacting guardians when students disengaged (teacher C and teacher G). Motivational strategies included verbal praise and private encouragement (teacher A and teacher I).

Flexibility emerged as a key strategy: teachers offered alternative submission formats such as voice, video, or text, mobile-friendly materials, and flexible deadlines (teacher D and teacher H). Teachers also proactively remediate students' technical skills. Teacher A noted: "I meet students individually to troubleshoot and train them on the platforms." Teacher F confirmed: "The main problems are technical: training students solves most of them."

Several teachers proposed institutionalizing preparedness for future disruptions. Teacher C suggested: "Allocate one day per week for remote learning, even without weather closure, to build students' online learning skills." This recommendation reflects teachers' recognition that digital readiness must be developed proactively, not only during emergencies.

These support strategies are best understood not as a freestanding set of practices but as direct responses to the specific challenges identified before. Student technical training addressed technical barriers; family engagement and flexible submission formats addressed disparities in access and home support; and the proposal to institutionalize weekly remote-learning practice directly targets the workload strain associated with treating ERT as a rare emergency response rather than a routine capability. This correspondence suggests that teachers' adaptive strategies emerged reactively, shaped by which challenges they encountered most directly, rather than from a comprehensive proactive framework. Notably, no comparable strategy emerged for assessment authenticity: while teachers described shifting toward project-based and oral assessment as a partial workaround, none reported a durable solution to verifying independent work remotely. This gap indicates that future preparedness efforts—including the proposed weekly remote-learning days—would need to explicitly incorporate assessment design, which current teacher-driven adaptations have not yet been resolved.

The strategies teachers developed during weather-related ERT reflect the integration of technological, pedagogical, and CK described in the TPACK framework (Mishra & Koehler, 2006). Teachers who successfully navigated the transition demonstrated growth in their TK, using platform features for communication, feedback, and flexible submission. More importantly, they developed TPK—understanding how to use technology to support student learning, motivation, and engagement. For science teachers, integrating virtual laboratories and digital resources into instruction required TPACK—the intersection where technology, pedagogy, and science content converge.

Through the lens of the CoI model (Garrison et al., 2000), teachers enacted strong teaching presence through communication, personalization, and flexibility. By following up with students via platform messaging, providing timely feedback, and adapting to individual circumstances, teachers maintained the design and facilitation elements essential to effective online instruction. Their efforts to engage families and build students' digital skills supported social presence by extending the learning community beyond the virtual classroom. These strategies also facilitated cognitive presence by ensuring students could access, engage with, and construct understanding of science content despite the challenges of remote learning.

From a constructivist perspective (Bruner, 1961; Vygotsky, 1978), the teachers' developmental approach — training students and orienting families — aligns with the principle of scaffolding. Rather than assuming students could independently navigate online learning, teachers recognized the need to build foundational skills progressively. This scaffolded approach supports learner autonomy and self-regulation, enabling students to take increasing responsibility for their own learning over time.

The proposal to institutionalize periodic remote learning days reflects teachers' forward-thinking approach to preparedness. Trust and Whalen (2020) found that teachers who had prior experience with online or blended teaching were better equipped to navigate ERT. By integrating regular remote instruction into the school calendar—even during normal conditions—schools could build both teacher and student capacity for future disruptions. This proactive approach aligns with Macias et al.'s (2022a) observation that sustained blended practices can strengthen digital readiness across the educational community.

DISCUSSION AND CONCLUSIONS

Summary of Key Findings

Regarding pedagogical adaptations (**RQ1**), teachers primarily transferred familiar strategies to the online environment while incrementally integrating digital tools though many reported constraints on hands-on activities and collaborative learning. Concerning student learning and performance (**RQ2**), outcomes were mixed: some students developed greater autonomy and self-regulation, while others exhibited passive participation. Teachers also expressed concerns about assessment authenticity. With respect to challenges (**RQ3**), four interconnected obstacles emerged: technical barriers, workload pressures, assessment validity concerns, and equity gaps in home learning environments. Finally, regarding lessons for future practice (**RQ4**), teachers recommended proactive digital literacy development, family engagement, flexible assessment approaches, and institutionalizing periodic remote learning days.

These findings both align with and diverge from prior accounts of pandemic-related ERT. Consistent with earlier studies, teachers in this sample reported increased workload as a near-universal consequence of the transition to remote instruction (Iglesias-Pradas et al., 2021), and equity gaps tied to home access mirrored patterns documented during COVID-19 school closures (Golden et al., 2023). However, the pattern of presence disruption observed here departs notably from findings in longer-duration pandemic contexts. Erickson and Wattiaux (2021), studying undergraduate science students during sustained COVID-19 remote instruction, found that students perceived high teaching and cognitive presence, with only social presence meaningfully reduced. By contrast, teachers in the present study described cognitive presence—not only social presence—as consistently compromised across the findings related to all four RQs. Although differences in educational level and perspective caution against direct comparison, this divergence suggests that the short, sudden, and recurring nature of weather-related ERT may be more disruptive to sustained inquiry and knowledge construction than the extended, if difficult, adaptation period afforded by pandemic-era closures, in which teachers and students had time to establish routines that later sustained cognitive engagement.

Theoretical Contributions

This study makes several contributions to educational theory. First, it offers a temporal refinement of the TPACK framework by identifying a structural distinction in how TPK is drawn upon during brief, recurring disruptions as opposed to sustained ones. The existing ERT literature, developed primarily from pandemic-related school closures, implicitly treats TPACK as a capacity that develops responsively over the course of a disruption, as teachers accumulate experience, access PD, and iteratively refine their practice across months of remote instruction. Weather-related ERT does not allow for this developmental trajectory: closures are sudden, brief, and recurring, leaving teachers no meaningful window in which to build competence during the event itself. Consistent with this, the teachers in this study who navigated the transition most readily were those already equipped with relevant TPK—chiefly TPK, the integration of technology with pedagogical strategy, rather than the fuller TPACK intersection, which was invoked primarily in subject-specific contexts such as virtual laboratory use.

Teachers' own recommendation to institutionalize a weekly remote-learning day reflects an implicit recognition of this distinction: readiness, in this context, functions less as a competency developed during a disruption and more as a standing reserve that must be built and maintained between disruptions. This temporal reframing suggests that teacher preparedness models built on pandemic-ERT experience—which assume time for in-event adaptation—may not transfer to weather-related contexts, where preparedness must instead precede the event.

Second, the findings suggest a potential, context-specific extension to the CoI model by revealing an uneven pattern of resilience across its three presences during short-duration, recurring disruption. Across the findings related to the four RQs, teaching presence proved the most resilient; teachers consistently sustained it through structure, active facilitation, and flexible communication, even under significant constraint. Social and cognitive presence, by contrast, were the presences most consistently compromised, undermined repeatedly by the same structural conditions—equity gaps, reduced opportunities for hands-on and collaborative work, and assessment ambiguity—across every sub-question. This pattern suggests that the three presences are not uniformly vulnerable to emergency disruption: because teaching presence can be enacted individually by the teacher, it withstands sudden disruption comparatively well, whereas social and cognitive presence, which depend on sustained opportunities for interaction, inquiry, and reflection, may therefore be disproportionately eroded when those opportunities are abruptly and repeatedly interrupted.

Third, the findings suggest a context-specific insight: the preservation of constructivist principles under emergency conditions appeared to depend less on the availability of technology than on whether teachers introduced deliberate structure. Where teachers relied on students' spontaneous engagement, constructivist practices such as active exploration and collaborative meaning-making broke down; where teachers introduced structured, self-paced tasks or scaffolded routines, students showed evidence of autonomy and self-regulated learning. This suggests that constructivist pedagogy in emergency remote contexts is not simply harder to sustain—it may be contingent on a specific compensatory mechanism, deliberate task structure substituting for the spontaneous interaction ordinarily present in the physical classroom, that determines whether constructivist ideals survive the transition at all.

Implications

Implications for practice

Science teachers should develop repertoires of readily deployable digital alternatives for laboratory activities, inquiry-based investigations, and collaborative learning. Maintaining a library of virtual laboratory resources, simulation tools, and at-home experiment kits can reduce preparation time when unexpected closures occur. Teachers should also establish clear communication protocols with students and families, and practice flexible assessment strategies.

Implications for policy

Educational policymakers should formalize contingency plans that include scheduled remote learning days during normal conditions. Finally, investing in science-specific virtual learning resources would strengthen the educational ecosystem's resilience.

Implications for teacher education

Pre-service teacher education programs should include dedicated training on ERT. Prospective science teachers should develop competencies in virtual laboratory platforms, online inquiry facilitation, and remote assessment strategies. In-service PD should similarly address ERT readiness.

Limitations

First, the study drew on a small, purposive sample of eleven science teachers from a single geographic region (the Eastern Region of Saudi Arabia); while this sample size was appropriate for the study's exploratory qualitative aim and consistent with the principle of information power (Malterud et al., 2016), the findings should not be assumed to generalize to teachers in other regions, educational systems, or disruption contexts without further investigation. Second, data collection relied on a single method—semi-structured interviews—without triangulation across data sources, and member checking was not conducted. Third, the findings reflect teachers' perceptions of their own effectiveness and their students' learning, rather than independently measured instructional or learning outcomes; statements regarding what teachers "achieved" throughout this manuscript should accordingly be understood as reports of perceived effectiveness rather than demonstrated effectiveness. Finally, because this study focused specifically on weather-related closures, the extent to which these findings apply to other forms of ERT remains an open question, addressed further below.

Future Research Directions

First, comparative studies could examine whether the challenges identified here generalize across different types of emergency disruptions. Second, longitudinal research could track how teachers' TPACK develops through repeated exposure to ERT. Third, quasi-experimental studies could evaluate the effectiveness of specific interventions in improving science learning. Fourth, student-focused research could examine how weather-related ERT affects science achievement, attitudes toward science. Fifth, the qualitative findings of this study could inform the development of a structured survey instrument for administration to a larger and more geographically diverse sample of science teachers.

In conclusion, this study contributes to the science education literature by documenting Saudi secondary science teachers' experiences during weather-related ERT. linking teachers' lived experiences to established theoretical frameworks (TPACK, CoI, and constructivism), the study reveals how emergency conditions challenge the technological, social, and pedagogical foundations of effective science instruction.

As climate change increases the frequency and intensity of weather-related disruptions worldwide, the insights gained from Saudi science teachers' experiences may offer transferable insights for comparable educational settings or contexts experiencing similar short-term emergency disruptions. By investing more in technology infrastructure, developing teachers' emergency pedagogical competencies, creating science-specific virtual learning resources, and institutionalizing preparedness through regular remote learning practice, educational systems can better ensure that all students—regardless of circumstances—have access to high-quality science education. The lessons learned from weather-related ERT thus offer guidance not only for managing current disruptions but for building the adaptive capacity that will be essential in an era of increasing environmental and social uncertainty.

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APPENDIX A

Table A1. Codebook

Theme	Code	Definition	Example quote (pseudonym)
Pedagogical adaptations	Strategy continuity	Transfer of familiar in-class strategies (e.g., brainstorming, concept mapping, discussion, slides) to online ERT environments with minimal modification.	"I didn't change much, I used the same PowerPoint slides and the same structure as in class." (teacher B)
	Digital expansion	Introduction of flipped videos, multimedia elements, and quick online research tasks to enhance interactivity and engagement.	"I uploaded short videos before class; live time focused on discussion and problem-solving." (teacher G)
	Perceived constraints	Feeling restricted to lecture and discussion methods; difficulty implementing cooperative learning online.	"In distance learning, the strategies used are lecture and discussion. I feel restricted in using these strategies… I cannot apply all available strategies because learning is remote." (teacher A) Teacher B added, "Cooperative learning cannot be applied in distance learning. I use it in person—dividing students into groups or pairs but online it is not feasible."
	Virtual lab integration	Use of virtual lab tools to simulate science experiments and maintain student engagement.	"The virtual lab made distance learning efficient and enjoyable." (teacher F)
Student learning and performance	Passive participation	Students exhibit minimal verbal or visual engagement; limited teacher-student interaction.	"Many never turned on cameras or mics." (teacher E)
	Autonomy gains	Students demonstrate improved responsibility, independent learning, and time management through online assignments.	"For students, online learning increased responsibility; tasks before and during class gave them more time, raising the quality of learning." (teacher I) "We should raise awareness among students and families so students rely on themselves to access lessons, use platforms, and participate independently." (teacher G).
	Teacher digital growth	Teachers enhance their technological competence and digital pedagogy skills through ERT.	"Distance learning developed my technological skills and made me adapt." (teacher F)
Challenges of online science teaching	Technical barriers	Connectivity problems, limited device access, and inadequate digital literacy among students.	"Some families had only one computer, so they used phones or iPads." (teacher A)
	Workload and adaptation	Increased teacher workload, time pressure, and fatigue from lesson preparation, digital communication, and multitasking.	"I felt I was working all day preparing, teaching, and replying to messages from students and parents." (teacher K)
	Assessment authenticity	Difficulty verifying that students completed work independently; concern about copying or using search engines.	"I cannot be sure whether the answer shows understanding or is copied from somewhere." (teacher F)
	Student readiness and equity	Disparities in access, motivation, and home learning environments that affect participation and achievement.	"Some students share one device with siblings." (teacher H)
Support, communication, and future practices	Family involvement	Engaging parents or guardians to ensure student participation and accountability during ERT.	"We raised awareness among families for student independence." (teacher G)
	Motivation and flexibility	Using praise, private feedback, and flexible deadlines or formats (e.g., voice, video) to encourage students.	"I sent private encouragement and allowed voice or video submissions." (teacher A)
	Student tech training	Providing individual guidance to help students use online platforms effectively.	"I trained students to use the platforms properly." (teacher A)
	Weekly online practice	Suggesting one remote learning day per week to sustain digital skills and readiness for emergencies.	"One day per week online to prepare students." (teacher C)