Synchronizing Online Asynchronous Modules with Synchronous Peer Interaction: A Systematic Review of Blended Learning Designs in Science Teacher Education

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Abstract

Blended learning integrating asynchronous online modules with synchronous peer interaction shows promise for science teacher education, yet optimal synchronization patterns remain understudied. This systematic review synthesized empirical evidence on blended learning designs in science teacher education, examining synchronization models, learning outcomes, and implementation factors. Following PRISMA 2020 guidelines, five databases (ERIC, Scopus, Web of Science, PsycINFO, and Education Source) were searched, yielding 38 empirical studies published between 2013 and 2024. Quality appraisal used ROBINS-I and CASP tools; findings were organized through narrative synthesis by synchronization model, discipline, and geographic context. Three synchronization patterns emerged: sequential (42%), parallel (37%), and integrated (21%). Sequential models, where asynchronous foundational content preceded synchronous peer microteaching, demonstrated the strongest gains in reflective competency, collaborative skills, and digital literacy. Critical success factors included structured peer-feedback rubrics, facilitator modeling during synchronous sessions, and explicit learning pathways that connect both modalities. Programs in resource-constrained contexts achieved comparable outcomes when offline-accessible asynchronous content and strategically scheduled synchronous sessions were implemented. Physics education particularly benefited from simulation-based asynchronous instruction paired with synchronous pedagogical discussion. This review concludes that intentional synchronization, supported by sound theoretical design, structured feedback systems, and attention to infrastructure constraints, significantly enhances science teachers' reflective competency, collaborative skills, and digital literacy. Future research should prioritize longitudinal studies tracking competency transfer to classroom practice, head-to-head model comparisons, and cost-effectiveness analyses.

Keywords: Blended learning, Asynchronous-synchronous synchronization, Science teacher education, Peer microteaching, Systematic review

INTRODUCTION

Quality teacher education is essential for achieving educational equity and excellence globally. Contemporary science education requires teachers who possess integrated competencies: reflective practice to examine their teaching critically (Schön 1983), collaborative skills to work effectively with colleagues and students (Vygotsky 1978), and digital literacy to leverage technology pedagogically (Mishra & Koehler 2008). From a pedagogical perspective, blended learning that combines asynchronous online modules with synchronous peer interaction should, in theory, maximize learning benefits. Asynchronous learning enables self-paced, flexible engagement with content and reflection

(Garrison & Kanuka 2004), while synchronous peer microteaching leverages immediate social feedback and collaborative meaning-making (Bonk & Graham 2012). When deliberately synchronized, these modalities should scaffold development of reflective capacity, collaborative competency, and digital fluency essential for 21st-century science educators.

In practice, teacher education implementation often falls short of this ideal. A comprehensive review of online teacher education noted that most programs operate primarily asynchronously, with minimal structured synchronous peer interaction (Martin & Bolliger 2018). In Southeast Asia, Sub-Saharan Africa, and other resource-limited contexts, infrastructure constraints—such as limited bandwidth, inconsistent internet access, and device scarcity—severely hamper both online and blended implementations (Thinley & Tshering 2021). Research on massive open online courses (MOOCs) for teacher professional development reports completion rates around 12%, partly attributed to a lack of community, immediate feedback, and peer support (Shah 2020). Science teacher education specifically remains underfunded globally, with limited evidence on how to optimally integrate online and in-person modalities in resource-constrained contexts (Potvin & Hasni 2014). Furthermore, peer feedback mechanisms in online settings often lack structured assessment tools, leading to superficial comments rather than deep, reflective dialogue (Nicol et al. 2014). The field thus faces a significant theory-practice gap regarding optimal synchronization of asynchronous and synchronous components in science teacher education.

While individual reviews exist on asynchronous learning, microteaching, and generic blended learning, no comprehensive systematic review specifically examines synchronization patterns between asynchronous modules and synchronous peer interaction in science teacher education. This is a critical gap because: (1) optimal design ratios and timing remain unclear; (2) mechanisms by which synchronization affects reflective and collaborative learning are theoretically underdeveloped; (3) discipline-specific affordances in physics, chemistry, and biology education are underexplored; and (4) effectiveness in resource-constrained settings differs substantially from developed countries yet remains understudied. This systematic review directly addresses this gap by synthesizing empirical evidence on blended asynchronous-synchronous learning designs in science teacher education, examining implementation patterns, effectiveness on learning outcomes, and contextual factors affecting success.

This systematic review aims to: (1) identify and synthesize empirical studies of blended learning integrating asynchronous online modules with synchronous peer microteaching in science teacher education; (2) characterize synchronization models employed (sequential, parallel, or integrated designs); (3) evaluate effectiveness on learning outcomes including reflective competency, collaborative skills, and digital literacy; (4) identify implementation facilitators and barriers, with particular attention to resource-constrained contexts; and (5) provide evidence-based recommendations for blended design in science teacher education globally.

LITERATURE REVIEW

Theoretical Foundations of Blended Learning

Blended learning, defined as the integration of face-to-face and online instruction (Bonk & Graham 2012), has emerged as a promising educational approach over the past two decades. Garrison and Kanuka (2004) conceptualize blended learning as a deliberate combination of asynchronous and synchronous interaction designed to achieve complementary pedagogical objectives. Unlike earlier models that simply combined modalities without strategic coordination, contemporary blended learning emphasizes intentional synchronization, in which asynchronous and synchronous components serve distinct yet complementary roles within an integrated learning ecosystem. The theoretical rationale for blending modalities rests on the notion that different instructional modes activate different cognitive and social processes. Asynchronous learning provides cognitive scaffolding through repeated access to content, supports metacognitive development through self-paced reflection, and enables equitable access regardless of geographic location or scheduling constraints (Garrison & Kanuka 2004). Synchronous interaction, conversely, activates social constructivist learning through real-time collaborative meaning-making, provides immediate feedback loops, and creates social presence that enhances motivation and accountability (Bonk & Graham 2012; Anderson 2008). The integration of both modalities should, in theory, maximize the pedagogical benefits of each while mitigating their individual limitations.

Reflective Practice in Teacher Education

Schön's (1983) seminal work on reflective practice established that professional learning, particularly in teaching, requires systematic reflection on experience. Reflective practice involves deliberate examination of teaching actions, underlying assumptions, and alternative approaches—processes Schön termed "reflection-in-action" and "reflection-on-action." For teacher education, this framework suggests that effective professional development must create structured opportunities for teachers to analyze their teaching, receive feedback, and consider pedagogical alternatives (Brookfield & Preskill 2005). Mezirow's (1997) transformative learning theory extends this perspective, positing that deep learning occurs when individuals examine disorienting dilemmas that challenge existing frames of reference, leading to perspective transformation. In the context of blended teacher education, this suggests that combining asynchronous exposure to diverse teaching approaches with synchronous peer feedback and discussion creates conditions for the examination and transformation of perspectives. However, research demonstrates that reflection does not occur automatically; it requires explicit scaffolding through prompts, guided questions, and facilitated dialogue (Nicol et al. 2014). This finding underscores the importance of intentional synchronization, in which asynchronous content provides the experiential basis and synchronous interaction provides structured facilitation for meaningful reflection.

Collaborative Learning and Social Constructivism

Vygotsky's (1978) sociocultural theory posits that learning is fundamentally social, occurring through interaction within the zone of proximal development, where more capable peers or mentors provide scaffolding. Collaborative learning leverages this principle by creating structured peer interaction through which learners co-construct knowledge (Johnson & Johnson 2009). In online contexts, peer collaboration has been theorized as particularly important because it counters the social isolation often experienced in purely asynchronous settings (Moore & Kearsley 2011). However, the quality of peer interaction matters substantially. Nicol et al. (2014) demonstrate that peer feedback in online settings often proves ineffective because peers lack clear quality standards, receive insufficient training, and face accountability gaps. This suggests that blended designs integrating asynchronous preparation (in which peers can review materials and prepare) with synchronous facilitated discussion (in which facilitators model high-quality feedback) may overcome these limitations. Wenger's (1998) communities of practice framework further suggests that sustained peer learning benefits from ongoing community engagement combining both regular interaction (synchronous) and accessible knowledge repositories (asynchronous), supporting the case for thoughtful blending.

Digital Literacy and TPACK in Science Education

The Technological Pedagogical Content Knowledge (TPACK) framework, developed by Mishra and Koehler (2008), identifies integrated competence in technology, pedagogy, and content knowledge as essential for effective teaching in digital contexts. Critically, TPACK is not simply additive (technology, pedagogy, and content) but represents unique knowledge at the intersections of these domains—understanding how to leverage specific technologies to teach particular content using sound pedagogy. Science education specifically requires TPACK competency because many scientific phenomena are best understood through computational visualization, simulation, or data analysis (Potvin & Hasni 2014). However, developing TPACK is non-trivial; research demonstrates that exposure to technology alone does not generate TPACK, nor does generic technology training produce disciplinary application (Koehler et al. 2015). Effective TPACK development requires situated learning in which teachers engage with technologies within their disciplinary context, receive feedback on their pedagogical technology integration, and develop their understanding through guided practice

(Mishra & Koehler 2008). Blended learning designs that scaffold asynchronous technology learning with synchronous disciplinary application have theoretical potential to address this challenge, though empirical evidence remains limited.

Microteaching as Peer Learning

Microteaching, defined as brief teaching episodes in simulated or low-stakes classroom contexts where teachers receive detailed feedback on their instruction, has long been recognized as valuable in teacher preparation (Bransford et al. 2015). Microteaching provides safe spaces for practice, enables videotaping for self-analysis, and creates opportunities for peer observation and feedback—all of which support reflective practice development. Peer microteaching extends this further by positioning peers, rather than only instructors, as observers and feedback-givers, thereby leveraging collaborative learning principles. However, the quality of peer feedback varies substantially depending on structure and training (Nicol et al. 2014). Research demonstrates that rubric-guided feedback produces higher-quality comments than unstructured peer observation (Brown et al. 2014), and that peer feedback combined with facilitator modeling yields better outcomes than peer feedback alone (Brookfield & Preskill 2005). These findings suggest that blended designs integrating asynchronous access to exemplary microteaching videos with synchronous facilitated peer feedback could optimize the benefits of peer microteaching while addressing quality concerns.

Blended Learning in Resource-Constrained Contexts

While blended learning shows promise, its implementation in resource-constrained contexts presents distinct challenges. Infrastructure limitations—unreliable internet connectivity, limited access to devices, and insufficient power availability—fundamentally constrain synchronous online interaction (Thinley & Tshering 2021). Research from Sub-Saharan Africa, South Asia, and Southeast Asia shows that purely online synchronous programs experience substantial dropout rates when bandwidth limitations prevent participation (Suhirman 2020). However, emerging evidence suggests thoughtful asynchronous design can mitigate these constraints. Offline-accessible asynchronous content, text-based formats, low-bandwidth design principles, and community-based synchronous participation hubs enable blended learning in resource-limited settings (Thinley & Tshering 2021). Cost-effectiveness is another consideration: while some argue that blended learning reduces costs through online delivery, high-quality blended design requires substantial investment in platform development, facilitator training, and technical support. Therefore, resource-constrained contexts require particular attention to implementation costs, teacher workload, and sustainability—factors often overlooked in research conducted in developed countries.

Research Gaps and Review Objectives

While substantial research exists on asynchronous online learning, synchronous peer teaching, and generic blended learning, several significant gaps persist. First, few reviews comprehensively examine how asynchronous and synchronous components should be sequenced and coordinated. Second, mechanisms by which synchronization patterns affect reflective and collaborative competency remain theoretically underdeveloped. Third, discipline-specific effectiveness in science teacher education is underexplored—most blended learning research spans general education. Fourth, implementations in resource-constrained contexts are sparse, limiting generalizability across most of global teacher education. Fifth, long-term effects beyond program completion receive limited attention. This systematic review addresses these gaps by synthesizing empirical evidence on intentional asynchronous-synchronous synchronization in science teacher education, examining which patterns prove most effective for reflective, collaborative, and digital competency development, and identifying implementation success factors, particularly in resource-limited contexts.

METHOD

This systematic review followed PRISMA 2020 guidelines (Page et al. 2021). Searches were conducted across five databases—ERIC, Scopus, Web of Science, PsycINFO, and Education Source—during August 2024. Search terms combined core concepts: (asynchronous OR "online module" OR "self-paced learning" OR MOOC) AND (synchronous OR "peer teaching" OR "peer feedback" OR microteaching) AND ("science teacher" OR "physics teacher" OR "chemistry teacher" OR "biology teacher" OR "STEM teacher education" OR "initial teacher education"). Filters applied: English language, peer-reviewed, publication years 2013–2024. The extended timeframe captured foundational studies while emphasizing 2020–2024 to reflect contemporary contexts.

This study included studies (1) empirical research (randomized controlled trials, quasi-experimental designs, case studies, design research); (2) explicit integration of asynchronous online content AND synchronous peer/group interaction within one program; (3) focus on pre-service or in-service science teachers; (4) measurement of at least one learning outcome (competency, engagement, satisfaction); (5) published in English peer-reviewed journals or conference proceedings with sufficient methodological detail. Otherwise, this study excluded studies (1) student learning without explicit teacher education focus; (2) purely asynchronous or purely synchronous programs without integration; (3) opinion articles, editorials, or literature reviews; (4) insufficient outcome data; (5) studies without explicit description of both blended design components.

Title and abstract screening was completed independently by two reviewers with interrater reliability assessment (Cohen's kappa = 0.81). Full-text review of identified articles was conducted using the inclusion criteria, with third-reviewer arbitration when needed. Final sample: n=38 published empirical studies meeting all criteria.

Structured data extraction captured: study design type, country/geographic region, participant characteristics (sample size, teaching discipline, experience level), intervention details (asynchronous and synchronous components, program duration, assessment tools), reported outcomes and measurements, and implementation context (resource level, technology access, infrastructure). Study quality was appraised using the ROBINS-I tool for quasi-experimental studies and the CASP criteria for case studies (Sterne et al. 2019; CASP 2020). Two reviewers independently assessed quality; disagreements were resolved through consensus discussion.

Given substantial heterogeneity in interventions and outcomes, narrative synthesis was employed following established methodology (Popay et al. 2006). Studies were organized by: (1) synchronization model (sequential, parallel, or integrated); (2) teaching discipline (physics, chemistry, biology, general science); (3) geographic context (developed vs. resource-constrained). The synthesis examined theoretical mechanisms linking synchronization design to competency outcomes and identified implementation factors that affect success or failure.

RESULTS AND DISCUSSION

Database searches yielded 1,423 unique records. After title and abstract screening, 68 full-text articles advanced to review. Following a detailed assessment against the inclusion criteria, 38 studies met the final inclusion criteria. Studies spanned publication years 2013–2024, with 74% (n=28) published 2020–2024. Geographic distribution: Europe n=14 (37%), Asia n=10 (26%), North America n=9 (24%), Oceania n=3 (8%), Africa n=2 (5%). Teaching disciplines: physics n=15 (39%), general science n=12 (32%), chemistry n=7 (18%), biology n=4 (11%). Study designs: quasi-experimental n=18 (47%), case study n=14 (37%), design research n=4 (11%), mixed-methods n=2 (5%).

Research Gaps and Review Objectives

Three primary synchronization patterns emerged from the synthesized evidence. They are the sequential, parallel, and integrated models.

Sequential Model (n=16, 42%): Asynchronous foundational content delivered first (typically 4–6 weeks), followed by synchronous peer microteaching (2–4 weeks). Participants engaged with asynchronous modules comprising video lectures, practice problems, interactive simulations, and case materials before engaging in live peer teaching and structured feedback. This design presumes that foundational knowledge developed asynchronously supports more advanced synchronous peer interaction.

Parallel Model (n=14, 37%): Asynchronous and synchronous components operated concurrently throughout the entire program. Participants accessed asynchronous modules weekly while simultaneously participating in bi-weekly or weekly synchronous peer sessions. This design assumes participants can manage both modalities simultaneously while maintaining engagement with both.

Integrated Model (n=8, 21%): Asynchronous artifacts (e.g., recorded peer teaching videos) directly informed and scaffolded synchronous peer analysis and discussion. Synchronous sessions were explicitly designed to analyze, discuss, and reflect upon asynchronous products. This design creates functional interdependence between modalities.

Learning Outcomes

Twenty-seven studies assessed reflective competency through reflective portfolios, video self-analysis, reflective journals, or self-assessment scales. Programs incorporating structured reflection prompts in synchronous discussions (n=19) showed greater improvements in reflective thinking than asynchronous reflection alone. Sequential models particularly supported the development of critical reflection on teaching, as foundational asynchronous content provided cases and examples that preceded guided synchronous reflection with peers. The theoretical framework of reflective practice (Schön 1983) was best operationalized when asynchronous content provided materials for reflection and synchronous sessions provided structured peer dialogue and facilitator guidance.

Twenty-four studies measured collaborative skills through peer feedback quality assessment, discussion depth analysis, or interdependence measures. Synchronous peer microteaching with structured feedback rubrics (n=16) demonstrated substantially greater development of collaborative competency than asynchronous peer feedback without synchronous scaffolding. Real-time interaction enabled immediate feedback, discussion of ambiguities, and negotiation of meaning (Garrison & Kanuka 2004). Studies consistently found that peer feedback became more substantive and constructive when embedded in synchronous discussion, particularly when facilitators modeled high-quality feedback and reflective dialogue. Parallel models showed moderate collaborative gains when synchronous sessions were well structured and included clear peer interaction protocols.

Twenty-two studies assessed technology competency, TPACK (Technological Pedagogical Content Knowledge), or digital citizenship. Sequential models where asynchronous modules explicitly taught technology tools and platform affordances before synchronous application (n=11) showed the largest gains in digital literacy. For example, teachers learned to navigate learning management systems, use video annotation tools, and follow discussion protocol standards through asynchronous tutorials, then applied these tools in synchronous peer microteaching sessions. Parallel models generated moderate digital literacy development. Notably, programs implemented in resource-rich contexts with high-bandwidth tools showed slightly larger gains in digital literacy. However, programs with low-bandwidth, mobile-friendly asynchronous designs still produced meaningful competency development, suggesting design flexibility supports equity.

Implementation Context and Effectiveness

Twelve studies (32%) explicitly implemented blended learning in resource-limited contexts, including Sub-Saharan Africa, South Asia, and Southeast Asia. Consistent success factors included: (1) asynchronous content accessible offline via downloaded modules or text-based materials; (2) synchronous sessions scheduled strategically around teachers' work schedules and local internet availability windows; (3) mobile-first design minimizing data requirements; (4) community-based participation hubs enabling group access when individual access was limited. A case study from Bhutan (Thinley & Tshering 2021) described asynchronous modules distributed via offline downloads, with weekly synchronous sessions conducted via mobile hotspots, achieving learning outcomes comparable to those in developed-context implementations. Studies from Kenya, Uganda, and Bangladesh emphasized that offline-accessible asynchronous content was critical to the sustainability of participation. Notably, programs that experienced implementation challenges typically either ignored offline accessibility requirements or scheduled synchronous sessions at inconvenient times for teachers' working hours.

Physics education (n=15 studies) showed particular effectiveness with asynchronous simulation-based concept instruction followed by synchronous problem-solving and peer microteaching. Researchers noted that asynchronous interactive simulations and visualizations allowed extended exploration of phenomena at the learner's pace, while synchronous sessions supported productive struggle, peer explanation of concepts, and pedagogical reasoning. Chemistry and biology implementations similarly benefited but with somewhat different patterns—laboratory design and phenomenon visualization sometimes leveraged asynchronous video demonstrations followed by synchronous collaborative peer design of instructional approaches. The discipline-specific affordances suggest that optimal synchronization patterns should reflect the discipline's epistemology and established pedagogical norms in the subject matter.

Implementation Facilitators and Barriers

Successful blended implementations consistently shared these characteristics: (1) explicit learning sequences connecting asynchronous to synchronous activities with clear expectations (n=24 studies); (2) structured peer feedback rubrics with clear quality criteria and anchors (n=20 studies); (3) facilitator presence during synchronous sessions, modeling quality feedback and reflective discussion (n=18 studies); (4) asynchronous content workload kept focused and manageable (4–6 hours per week, n=16 studies); (5) offline-accessible asynchronous components supporting equitable access (n=12 low-resource studies). Programs incorporating these features reported significantly higher engagement rates and achievement of learning outcomes.

Implementation barriers included: (1) technology access inconsistency, particularly in low-resource regions where infrastructure remained unreliable (n=12 studies); (2) asynchronous content overload causing participant dropout—programs assigning greater than 8 hours weekly asynchronous work reported higher attrition (n=9 studies); (3) scheduling difficulties for synchronous sessions across geographic time zones or conflicting with teaching schedules (n=6 studies); (4) inadequate preparation of peer facilitators, resulting in low-quality feedback (n=8 studies); (5) lack of accountability mechanisms in synchronous participation (n=7 studies). Programs that did not systematically address these barriers reported significantly lower completion rates and diminished learning outcomes.

Discussion

The synthesized evidence demonstrates that intentional synchronization of asynchronous and synchronous components operates through multiple theoretically distinct but interconnected mechanisms. At the cognitive level, asynchronous content enables self-paced processing and deep encoding of foundational concepts, creating the knowledge foundation necessary for higher-order synchronous peer interaction (Garrison & Kanuka 2004). However, asynchronous learning alone does not reliably foster reflection; our finding that programs with explicit synchronous reflection prompts achieved greater gains in reflective competency aligns with Mezirow's (1997) transformative learning theory, which posits that perspective change requires not just exposure to disorienting content but also structured dialogue to examine and reframe assumptions. The synchronous peer interaction component activates this reflective dialogue, while the asynchronous content provides the experiential material for reflection.

At the social level, Vygotsky's (1978) sociocultural theory predicts that synchronous peer interaction within zones of proximal development facilitates collaborative learning. Our finding that structured peer feedback (with rubrics and facilitator modeling) outperformed unstructured peer interaction aligns with this theory—the rubrics and facilitator modeling provide the external scaffolding necessary for peers to perform at higher levels (Nicol et al. 2014). Furthermore, the finding that asynchronous peer video repositories enhanced synchronous discussion suggests that combining modalities activates multiple social processes: asynchronous exposure enables observational learning and preparation, while synchronous discussion enables collaborative interpretation and meaning-making. This combination may be more developmentally powerful than either modality alone.

For digital literacy development, the strong effect of sequential models (where asynchronous tool tutorials preceded synchronous application) suggests that TPACK development (Mishra & Koehler 2008) benefits from scaffolded complexity. Teachers first develop technical proficiency asynchronously in low-stakes contexts, then apply this knowledge synchronously with peer support and facilitator feedback in authentic disciplinary applications. This scaffolding may activate situated learning mechanisms (Lave & Wenger 1991), in which technological knowledge is developed not in abstract contexts but within authentic disciplinary practice.

Our findings reveal meaningful differences in effectiveness across synchronization models, though with important nuances. Sequential models (asynchronous foundational → synchronous application) showed consistently strong results across reflective competency, collaborative skills, and digital literacy. This consistency suggests that sequential designs optimally leverage the affordances of each modality: asynchronous content enables individual processing and foundational knowledge development without social performance pressure, while synchronous peer interaction builds upon this foundation. However, sequential models require longer program duration and assume participants lack prior foundational knowledge—assumptions that may not hold for in-service teachers with substantial teaching experience.

Parallel models (concurrent asynchronous and synchronous) generated moderate but consistent positive outcomes. Our analysis suggests that parallel models work particularly well when synchronous sessions explicitly connect to asynchronous materials (e.g., synchronous discussions directly addressing asynchronous concepts), but fail when asynchronous and synchronous components operate independently. The finding that cognitive load theory (Sweller 1988) predicts cognitive overload when simultaneous demands exceed working memory capacity aligns with our observation that participants in parallel models sometimes experienced confusion about which modality addressed which learning objective. Programs that explicitly scaffolded this coordination (clear synchronous prompts to review specific asynchronous materials before discussion) mitigated this challenge.

Integrated models (in which asynchronous artifacts directly feed into synchronous analysis) showed smaller effect sizes but strong qualitative feedback on engagement and perceived relevance. Integrated designs create authentic synchronous learning because discussion focuses on actual peer-generated teaching artifacts rather than abstract content. However, integrated models require sophisticated technical implementation (video hosting, annotation tools, asynchronous submission systems) and sophisticated pedagogical design (facilitators must prepare analysis prompts based on submitted artifacts). The smaller effect sizes may reflect implementation challenges rather than theoretical limitations; poorly implemented integrated models showed substantial dissatisfaction, whereas well-implemented models achieved high engagement despite modest gains in effect size.

Our finding that physics education yielded stronger outcomes (particularly with simulation-based asynchronous learning) suggests that synchronization patterns should reflect the discipline's epistemology. Physics education uniquely benefits from interactive visualization and simulation technologies that enable extended experimentation with phenomena—affordances particularly well suited to asynchronous, self-paced contexts (Potvin & Hasni 2014). Synchronous peer discussion then serves to support pedagogical reasoning about how to teach these phenomena, rather than to teach the concepts themselves. Chemistry and biology implementations, which less frequently leverage sophisticated simulations, showed different patterns—sometimes using asynchronous video demonstrations followed by synchronous collaborative design of laboratory or field investigations. This disciplinary variation suggests that one-size-fits-all blended designs may be suboptimal; effective synchronization should reflect the discipline's epistemological structures and typical pedagogies.

Geographic context similarly moderated effectiveness. Programs in resource-rich contexts with reliable infrastructure and multiple technology options showed slightly larger effect sizes, consistent with technology adoption theory (Rogers 2003), which predicts that technology-enhanced interventions work best when infrastructure enables optimal implementation. However, remarkably, programs in resource-constrained contexts achieved comparable learning outcomes when designed with offline-accessible asynchronous components and strategic synchronous scheduling. This finding has important equity implications: effective blended learning need not require expensive infrastructure if thoughtfully designed. However, this finding also highlights that implementation in low-resource contexts requires different design principles (offline-first, text-light, community-based synchronous hubs) than developed-context implementations.

Our analysis revealed that facilitator presence during synchronous sessions was a strong mediator of outcomes. Programs in which facilitators modeled quality feedback, demonstrated reflective questioning, and provided structure for peer discussion achieved substantially higher learning gains than programs that relied entirely on peer-to-peer interaction (Brown et al. 2014). This finding aligns with expert apprenticeship and cognitive apprenticeship models (Collins, Brown, & Newman 1989), in which experts make their implicit knowledge and processes visible through modeling and gradually transfer responsibility to learners. In the context of blended learning, facilitators serve to bridge asynchronous individual learning and synchronous peer learning by modeling how to apply content learned asynchronously in synchronous peer discussion.

Furthermore, the finding that structured peer feedback rubrics substantially improved feedback quality suggests that peer learning is not inherently unequal in quality to facilitator feedback, provided the structure, training, and accountability are established. This has important implications for scaling blended programs in under-resourced contexts where experienced facilitators may be scarce; structured approaches that enable qualified peer facilitation may offer scalable alternatives to facilitator-heavy models.

While our review demonstrates that blended asynchronous-synchronous learning yields meaningful gains in reflective competency, collaborative skills, and digital literacy, important limitations warrant discussion. First, most studies compare blended interventions to traditional instruction rather than comparing synchronization models directly via randomized controlled trials. Therefore, while we can conclude that blended learning is effective, causality regarding optimal synchronization patterns remains partially inferential. Second, heterogeneity in outcome measurement makes meta-analytic comparison difficult; studies used diverse instruments to assess reflective competency, collaborative skills, and digital literacy. Third, publication bias may inflate effect estimates; non-significant or implementation-failure studies may be underrepresented in published literature, particularly for resource-constrained contexts.

Fourth, longitudinal data extending beyond program completion remain rare. Most studies measure immediate post-program outcomes without assessing whether developed competencies persist, transfer to classroom practice, or influence student learning. This gap limits conclusions about long-term effectiveness and practical significance. Fifth, individual differences in learner characteristics (prior technology experience, reflective capacity, learning preferences, motivation) emerged as important moderators in several studies, yet systematic investigation of individual-difference interactions remains limited. Sixth, cost-effectiveness data are entirely absent from the literature; while blended programs may be effective, their cost relative to alternative professional development approaches has not been studied.

For educational leaders designing science teacher education programs, this review suggests several actionable implications. First, blended learning that integrates asynchronous and synchronous components shows genuine promise for developing reflective, collaborative, and digital competencies—improvements that are difficult to achieve through single-modality approaches. However, implementation quality critically matters; poorly designed blended programs underperform compared to well-designed traditional approaches. Second, the selection of a synchronization model should reflect the program context and learner characteristics. Sequential models suit pre-service teachers who require foundational knowledge; parallel models suit experienced teachers managing ongoing professional development; integrated models maximize relevance but require sophisticated implementation. Third, investment in facilitator training and peer feedback structure substantially improves outcomes—this should receive priority in implementation planning.

Fourth, resource constraints need not prevent effective blended learning if designs explicitly address infrastructure limitations. Offline-accessible asynchronous content, text-light design principles, strategic synchronous scheduling, and community participation hubs enable blended learning in resource-limited contexts. This has important equity implications, as thoughtfully designed blended approaches may be more accessible to teachers in under-resourced regions than either expensive in-person programs or bandwidth-intensive pure online models. Fifth, programs should establish clear synchronization sequences and learning pathways, explicit about which asynchronous content precedes which synchronous activities and why. Ambiguous connections between modalities create confusion and reduce engagement.

Important research gaps remain. First, longitudinal research tracking competency development beyond program completion and into classroom practice would substantiate claims about practical significance. Follow-up studies assessing whether reflective competencies translate to reflective classroom practice, whether collaborative skills influence peer collegiality in schools, and whether digital literacy enables technology integration in teaching would strengthen the evidence base. Second, rigorous head-to-head trials directly comparing synchronization models (sequential, parallel, or integrated) under controlled conditions would definitively establish which designs are most effective under which circumstances. Third, mechanistic research using qualitative methods and learning analytics would illuminate the cognitive and social processes through which synchronization operates. Fourth, investigation of individual differences—which teachers benefit most from which synchronization models, how prior technology experience moderates effectiveness, what role motivation and learning preference play—would enable personalization. Fifth, cost-effectiveness studies comparing blended approaches to alternative professional development models would inform policy decisions about resource allocation. Finally, an expanded examination of implementations across diverse geographic and economic contexts would improve generalizability beyond the current concentrations in North America and Europe.

CONCLUSION

This systematic review of 38 empirical studies demonstrates that intentional synchronization of asynchronous online modules with synchronous peer microteaching significantly enhances science teachers' reflective competency, collaborative skills, and digital literacy. Sequential and integrated synchronization models showed the strongest overall effectiveness, particularly for reflective competency development. Parallel models, while generating meaningful gains, showed smaller effects when asynchronous-synchronous coordination remained loose or implicit. Critical success factors include: structured synchronization sequencing, peer feedback rubrics, facilitator support during synchronous sessions, managed asynchronous workloads, and—importantly for global reach—offline-accessible asynchronous content. Remarkably, programs implemented in resource-constrained contexts achieved outcomes comparable to those of implementations in developed contexts when designed with appropriate affordances for limited bandwidth and device access.

Future research should prioritize: (1) longitudinal studies tracking persistence and transfer of competencies into classroom practice; (2) mechanistic qualitative research explaining synchronization-outcome causal pathways; (3) head-to-head randomized trials comparing synchronization models; (4) expanded discipline coverage including chemistry and biology; (5) implementation and cost-effectiveness studies examining scalability; and (6) investigation of individual differences as moderating factors. Educational leaders implementing science teacher blended programs should adhere to evidence-based synchronization patterns, invest in structured peer feedback systems, and prioritize offline accessibility to maximize learning outcomes and educational equity globally. Intentional synchronization of asynchronous and synchronous modalities, when carefully designed and implemented, holds transformative potential for improving science teacher education worldwide. The evidence suggests that blended learning is not simply a convenience or cost-saving measure, but a genuinely pedagogically superior approach when designed with theoretical grounding, disciplinary sensitivity, and attention to implementation quality.

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This study was conducted in accordance with recognized ethical standards. Informed consent was obtained from all participants, and data were collected and reported in accordance with confidentiality and anonymity requirements.

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ChatGPT was used only for grammar refinement, academic style review, and reference-format checking. It was not used to generate, analyze, or interpret research data. The authors reviewed and approved the manuscript and take full responsibility for its content.

Conflicts of Interest Statement

The authors declare no conflicts of interest related to the research, authorship, or publication of this article.

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