

FROM SIGNAL THEORY TO DEPLOYABLE REAL-TIME EMBEDDED DSP:
A COMPARATIVE QUALITATIVE STUDY OF PERCEIVED GAPS IN
MATHEMATICAL READINESS FOR INDUSTRY ROLES IN PAKISTAN
AND THE UNITED KINGDOM

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Abstract

This study explored perceived gaps in mathematical readiness for real-time embedded Digital Signal Processing (DSP) roles among university students in Pakistan and the United Kingdom (UK). A qualitative comparative design was employed, and semi-structured interviews were conducted with 20 students, including 10 participants from each country. Reflexive thematic analysis identified five interrelated themes: gaps in fundamental mathematical knowledge, difficulty transferring theory to practical DSP applications, differences in educational and technological support, limited integration of artificial intelligence (AI), and misalignment between educational preparation and perceived industry expectations. Participants in both contexts reported familiarity with key mathematical principles but experienced difficulty translating concepts such as Fourier transforms, calculus, and linear algebra into algorithms, simulations, and real-time embedded implementations. Pakistani participants generally reported greater limitations in access to specialized laboratories, industry-standard software, embedded platforms, and industry-informed academic support, whereas UK participants described comparatively stronger resources but continued to experience theory–practice difficulties. AI was perceived as potentially useful for visualization, simulation, coding assistance, and feedback; however, its curricular integration remained limited and required greater emphasis on verification and mathematical reasoning. The findings highlighted the need to align mathematical instruction with simulation, programming, hardware implementation, authentic assessment, and industry-linked learning. The study provided context-sensitive recommendations for strengthening students' preparation for real-time embedded DSP roles.

1. Introduction

Real-time embedded Digital Signal Processing (DSP) is central to numerous technology-driven industries, including telecommunications, healthcare, automotive systems, aerospace, defense, and industrial automation. It enables digital signals to be acquired, analyzed, transformed, and processed within strict time, memory, and computational constraints. Contemporary DSP algorithms are widely used in telecommunications and wireless communication systems, where efficient processing is essential for filtering, signal detection, data transmission, and noise reduction (Sadeghi, 2025). Machine vision and deep-learning applications also rely on advanced signal-processing techniques to improve accuracy, automation, safety, and operational efficiency (Agrawal et al., 2025). The growing integration of embedded systems with sensors, communication networks, intelligent devices, and cyber-physical environments has further increased the demand for professionals who can design and implement reliable DSP solutions. Cyber-physical systems require the coordinated operation of computation, communication, and physical processes, making real-time processing competence increasingly important in modern industrial environments (Khalid, 2025). Consequently, professionals working with real-time embedded DSP systems require both technical competence and a strong mathematical foundation.

Concepts such as calculus, linear algebra, Fourier transforms, probability, signal theory, and numerical methods are essential for analyzing signals, designing algorithms, and implementing DSP solutions. However, understanding mathematical theory does not necessarily ensure that students can apply it effectively in practical settings. Students may be able to explain formulas and theoretical principles but still experience difficulty translating them into algorithms, simulations, programming procedures, and real-time embedded applications. This disconnect between conceptual understanding and practical implementation may affect their confidence and

perceived readiness for DSP-related industry roles. The present study explores and compares students' perceptions of their mathematical readiness for real-time embedded DSP roles in selected educational contexts in Pakistan and the United Kingdom (UK). Rather than objectively measuring students' mathematical competence, the study examines how participants describe their preparation, learning experiences, and challenges in applying mathematical concepts to practical DSP problems. It also investigates their perceptions of educational support, practical exposure, technological resources, and alignment between university education and industry expectations. Through this comparative inquiry, the study seeks to identify shared and context-specific challenges and to propose recommendations for strengthening DSP education.

1.1 Background of the Research

Real-time embedded DSP involves the mathematical analysis and computational processing of digital signals within predetermined time constraints. It is used in digital communication, speech recognition, biomedical monitoring, image processing, radar systems, autonomous vehicles, industrial control, and defense technologies. Successful implementation requires students to connect mathematical knowledge with programming, algorithm design, simulation, hardware limitations, and system-level problem-solving. Mathematical concepts such as Fourier analysis, calculus, linear algebra, probability, and discrete-time signal theory provide the foundation for understanding DSP algorithms. However, industry readiness requires more than theoretical familiarity with these concepts. Students must be able to interpret mathematical relationships, convert them into computational procedures, test their behavior through simulations, and implement them using appropriate software and embedded hardware. This transition from abstract knowledge to practical implementation represents an important challenge in DSP education.

The rapid development of artificial intelligence, advanced computation, communication systems, and cybersecurity has also transformed the knowledge and competencies expected from graduates of technical programmes (Kumar et al., 2026). Modern DSP professionals increasingly work in multidisciplinary environments in which mathematical reasoning must be combined with programming, machine learning, embedded systems, data analysis, and cybersecurity awareness. Universities must therefore ensure that students develop not only theoretical knowledge but also the ability to apply that knowledge within complex technological systems. Educational context may influence how students experience this transition. In Pakistan, the interaction between conventional teaching practices and emerging educational technologies can affect opportunities for students to connect theoretical knowledge with practical technical applications (Khan et al., 2025). Limited access to specialized laboratories, industry-standard software, embedded hardware, and instructors with relevant practical experience may further restrict students' exposure to real-time DSP applications. These conditions may contribute to perceived gaps between what students learn in classrooms and what they believe industry roles require.

Universities in the UK may provide greater access to technological infrastructure, specialized laboratories, project-based learning, and industry engagement. Nevertheless, the availability of educational resources does not automatically ensure that students can transfer mathematical knowledge to real-time DSP implementation. Students may still experience difficulty translating equations and theoretical models into algorithms that operate under practical computational constraints. The integration of technology into teaching must therefore be supported by appropriate pedagogical approaches that promote meaningful application rather than only theoretical understanding (Rehmat et al., 2025). The wider integration of emerging technologies into higher education presents both opportunities and challenges. Artificial intelligence, robotics,

and other technologies associated with the Fourth Industrial Revolution can support interactive, flexible, and technology-enhanced learning. However, their successful use depends on institutional infrastructure, curriculum design, faculty competence, and students' ability to use these technologies critically and effectively (Chaka, 2023). These factors are particularly relevant to DSP education, in which students need opportunities to connect mathematical principles with software-based simulations and hardware-oriented applications.

AI-enabled simulations, adaptive learning systems, automated feedback, and visualization tools may assist students in engaging with complex mathematical concepts. Research on AI in education indicates that technology can influence teaching confidence and instructional effectiveness, although its benefits depend on educators' readiness and ability to integrate it into learning activities (Ahmed, Faisal, et al., 2025). Faculty development is therefore essential because access to AI tools alone may not improve students' mathematical or technical preparation. The ethical and responsible use of AI is also important. Students may use generative AI systems to explain formulas, generate code, visualize signals, or troubleshoot algorithms. Nevertheless, excessive reliance on automatically generated solutions may weaken independent reasoning if students do not understand the underlying mathematics. Educational institutions must therefore develop learning practices that encourage students to use AI critically, ethically, and transparently (Ahmed, Urooj, et al., 2025). Within DSP education, AI should complement mathematical reasoning rather than replace it.

Against this background, comparing students' experiences in Pakistan and the UK can provide useful insights into shared and context-specific challenges. The present study investigates how participating students perceive their mathematical preparation, the difficulties they encounter when applying mathematics to real-time DSP problems, and the educational conditions that influence their perceived readiness for industry roles.

1.2 Problem Statement

A strong mathematical foundation is essential for designing, analyzing, and implementing real-time embedded DSP systems. However, students may complete relevant university courses without developing sufficient confidence or practical ability to apply mathematical principles in real-world DSP contexts. The problem may not be limited to inadequate theoretical knowledge; it may also involve difficulties in transferring that knowledge to algorithm development, simulation, programming, hardware implementation, and real-time problem-solving. Educational practices that emphasize formulas and theoretical examinations without providing sufficient opportunities for practical application may reinforce this gap. Such conditions can affect students' perceived professional readiness and their ability to respond to the technical expectations associated with DSP-related employment. Broader pedagogical and technological conditions may also influence how effectively students connect theoretical learning with practical technical tasks (Khan et al., 2025). Although Pakistan and the UK have different educational resources and institutional contexts, students in both settings may experience difficulties in applying mathematics to DSP. These challenges cannot be understood adequately through broad assumptions about the two national education systems. Instead, it is necessary to examine how students within selected institutions describe their learning experiences, access to practical resources, and preparation for real-time embedded DSP work. Differences in technology integration, teaching practices, laboratory exposure, curriculum design, and academic support may shape students' perceptions of readiness in different ways (Ahmed et al., 2025). The growing influence of AI and machine learning adds another dimension to this problem. While these technologies may support visualization, simulation, personalized learning, and algorithm development, their educational value depends on how effectively they are integrated into teaching and how well students understand the

mathematical principles underlying their operation (Rehmat et al., 2025). AI-supported learning may provide explanations and computational assistance, but it cannot compensate for weak conceptual understanding or insufficient practical experience.

The central problem addressed by this study is therefore the perceived gap between students' academic exposure to mathematics and their ability to apply that knowledge in real-time embedded DSP contexts. Without a clear understanding of nature and sources of this gap, universities may find it difficult to design curricula, teaching practices, laboratory activities, and industry partnerships that adequately prepare students for professional DSP roles.

1.3 Research Questions

This study seeks to answer the following research questions:

1. What gaps do participating students in Pakistan and the UK perceive in their mathematical readiness for real-time embedded DSP roles?
2. What challenges do students encounter when applying key mathematical concepts to practical and real-time DSP scenarios?
3. How do students perceive the influence of curriculum, teaching practices, technological resources, and practical exposure on their mathematical readiness?
4. What similarities and differences are evident between the experiences reported by participating students in Pakistan and the UK?

1.4 Research Objectives

The objectives of this study are:

1. To identify the gaps that participating students in Pakistan and the UK perceive in their mathematical readiness for real-time embedded DSP roles.
2. To explore the challenges students encounter when applying mathematical concepts to practical DSP problems and real-time embedded systems.
3. To examine students' perceptions of how curriculum, teaching practices, technological

resources, and practical learning opportunities influence their mathematical preparation.

4.To compare the shared and context-specific experiences reported by participating students in Pakistan and the UK.

5.To propose practical recommendations for improving mathematical preparation, experiential learning, and alignment between DSP education and industry requirements.

1.5 Significance of the Research

This study is significant because it focuses on the transition from mathematical theory to practical implementation in real-time embedded DSP education. Although mathematical concepts form the foundation of DSP, students' ability to recall or explain these concepts does not necessarily demonstrate their readiness to apply them in simulations, algorithms, or embedded systems. By examining students' experiences, the study provides a more detailed understanding of the difficulties that may arise during this transition. The comparison between participating students in Pakistan and the UK provides insights into challenges that may be shared across educational contexts, as well as those associated with differences in resources, teaching practices, laboratory exposure, and industry engagement. The study does not seek to generalize its findings to all universities in either country. Instead, it aims to develop a context-sensitive account of how students experience mathematical preparation within the institutions and programmes represented in the sample.

The findings may help universities review the alignment among mathematical instruction, DSP coursework, laboratory activities, assessment methods, and industry expectations. They may also support the development of practical teaching strategies that connect mathematical concepts with programming, simulation, algorithm testing, and hardware implementation. Such improvements could help students understand not only how mathematical principles are derived but also how they operate within real-time DSP systems. The study may also inform discussions

about the responsible integration of AI and emerging technologies into DSP education. AI-supported tools can potentially improve visualization, feedback, and interactive problem-solving, but they should complement rather than replace students' understanding of fundamental mathematical principles. The findings may therefore help educators determine how these tools can be incorporated while maintaining mathematical rigor, independent reasoning, and responsible technology use.

Finally, the study contributes to research on engineering education, mathematical preparedness, and graduate readiness by highlighting students' perspectives on the relationship between theory and practice. Its recommendations may assist curriculum designers, instructors, university administrators, and industry partners in developing more applied, interdisciplinary, and professionally relevant approaches to real-time embedded DSP education.

2. Literature Review

Real-time embedded Digital Signal Processing (DSP) requires professionals to combine mathematical reasoning, algorithmic knowledge, programming competence, and an understanding of hardware and computational constraints. DSP algorithms support numerous applications in telecommunications, wireless communication, healthcare, machine vision, industrial automation, autonomous systems, and defense technologies (Sadeghi, 2025). The expansion of cyber-physical systems has further increased the need for engineers who can connect mathematical models with real-time computational and physical processes (Khalid, 2025). Contemporary applications demonstrate that technical readiness cannot be developed through theoretical instruction alone. Machine-vision systems, for example, require professionals to integrate mathematical models, signal-processing algorithms, software, and application-specific requirements (Agrawal et al., 2025). Similarly, developments in artificial intelligence, computation, communication, and cybersecurity

increasingly require multidisciplinary technical competence (Kumar et al., 2026). These developments create pressure on universities to prepare students who can transfer mathematical knowledge from classroom settings to authentic DSP problems.

This literature review examines the theoretical foundations of the study, the role of mathematics in DSP, mathematical readiness within educational systems, the contribution of AI and emerging technologies, the importance of hands-on learning, and the value of interdisciplinary education and industry collaboration. It concludes by identifying the research gaps addressed by the present comparative qualitative study.

2.1 Theoretical Framework

The present study integrates Transfer of Learning and Situated Learning to explain how students move from mathematical knowledge to practical, real-time digital signal processing (DSP). Transfer of Learning emphasizes the application of knowledge across contexts, distinguishing relatively direct transfer from more demanding forms of far transfer (Barnett & Ceci, 2002). In DSP education, students may therefore understand mathematical concepts such as Fourier analysis yet struggle to apply them to unfamiliar problems involving sampling, noise, algorithm selection, coding, and real-time computational constraints. Technology can facilitate this transfer through visualization, simulation, and experimentation, although its effectiveness depends on pedagogical integration (Khan et al., 2025; Chaka, 2023).

Situated Learning emphasizes that knowledge develops through participation in authentic activities and contexts (Lave & Wenger, 1991; Brown et al., 1989). Accordingly, DSP readiness requires opportunities to engage with laboratories, simulations, programming, hardware, datasets, and real-time constraints. AI tools may further support authentic problem-solving through explanation, coding, visualization, and troubleshooting, provided students critically evaluate rather than passively depend on AI-

generated outputs (Ahmed, Urooj, et al., 2025). Together, these perspectives frame mathematical readiness as the ability to apply, contextualize, and operationalize mathematical knowledge within authentic DSP environments.

2.2 The Role of Mathematics in DSP

Mathematics provides the conceptual and computational foundation of DSP. Digital signals are represented, analyzed, modified, and reconstructed through mathematical operations. Fourier analysis allows engineers to examine the frequency components of signals, while calculus contributes to continuous-to-discrete modelling and the interpretation of changing systems. Linear algebra supports matrix-based operations, transformations, filtering, estimation, and multidimensional signal processing. Probability and statistics are essential for analyzing random signals, noise, uncertainty, and detection problems. DSP algorithms used in telecommunications and wireless communication depend on mathematical principles for filtering, modulation, coding, compression, spectral analysis, and signal reconstruction (Sadeghi, 2025). Students must therefore understand not only the formulas associated with these operations but also the assumptions, limitations, and practical consequences of applying them.

The mathematical demands of DSP become more complex in real-time embedded environments. An algorithm may be mathematically correct but unsuitable for implementation because it requires excessive processing time, memory, power, or numerical precision. Students must therefore learn to balance mathematical accuracy with computational efficiency. This requires an understanding of sampling, quantization, fixed-point arithmetic, finite word length, latency, stability, and algorithmic complexity. Applications in medical imaging demonstrate the importance of combining signal-processing theory with hardware and system-level requirements. Advanced imaging technologies rely on the coordinated processing of complex signals under technical and physical constraints (Dong, 2023). Machine-vision and

deep-learning systems similarly require mathematical models to be translated into efficient computational procedures (Agrawal et al., 2025).

Despite the importance of these concepts, students may struggle to connect abstract mathematics with DSP implementation. A student may understand a Fourier transform as an equation but remain uncertain about how to interpret frequency-domain output or apply the transform to a noisy signal. This suggests that mathematical readiness should not be defined only as knowledge of mathematical content. It should also include the ability to select, apply, interpret, and evaluate mathematical procedures in context.

2.3 Educational Systems and Mathematical Readiness

Universities play a central role in developing students' mathematical and technical readiness. Curriculum design, teaching practices, assessment methods, faculty competence, laboratory infrastructure, and industry engagement can all influence whether students learn mathematics as an isolated subject or as a practical tool for engineering problem-solving. In Pakistan, the relationship between traditional pedagogy and technology-integrated teaching remains an important concern. Research suggests that educational institutions must balance established instructional practices with meaningful uses of technology to improve student learning (Khan et al., 2025). In technical disciplines, an excessive emphasis on lectures, memorization, and written examinations may limit opportunities for students to apply mathematics through programming, simulation, experimentation, and hardware implementation.

AI-integrated pedagogies also depend on institutional leadership and faculty guidance. Teachers may require professional development and organizational support before they can use emerging technologies effectively in teaching and learning (Khan, Kausar, & Khan, 2025). This concern is relevant to DSP education because

instructors need both subject knowledge and technological competence to connect mathematical concepts with software, simulations, and embedded platforms. Research on generative AI in teacher education shows that learners interpret and experience AI in different ways depending on their educational context, expectations, and prior exposure (Ahmed, Ali, & Mansoor, 2025). Research also indicates that AI can influence teachers' confidence in using technology, although the effect depends on training, accessibility, and the perceived usefulness of the tools (Ahmed, Faisal, et al., 2025). These findings suggest that technological availability alone is not an adequate indicator of educational readiness.

The UK generally has more established technological infrastructure and stronger links between universities and industry. However, differences in resources do not necessarily eliminate the theory-practice gap. Students may have access to sophisticated software and laboratories but still struggle to connect mathematical principles with authentic real-time applications. Therefore, the relevant issue is not only whether resources are available but also whether curricula, teaching activities, and assessments require students to integrate mathematical reasoning with practical DSP implementation. The literature currently provides insufficient direct evidence for making broad national comparisons between Pakistan and the UK. Studies examining educational technology in Pakistan offer relevant contextual information, but they do not directly measure students' mathematical readiness for embedded DSP. Similarly, general observations about technologically advanced educational systems should not be treated as evidence that all UK students receive sufficient practical preparation. A focused comparison of students' experiences is therefore required.

2.4 AI and Technological Advancements in Education

AI and machine learning are influencing both DSP practice and technical education. In professional settings, AI is increasingly combined with signal processing to support pattern recognition, prediction, classification, automation, and intelligent decision-making. Developments in AI, communication, computation, and cybersecurity demonstrate the growing convergence of previously separate technical fields (Baig et al., 2021; Kumar et al., 2026). In education, AI can provide personalized explanations, automated feedback, adaptive exercises, simulations, visualizations, and programming assistance. These features may be especially useful when students are learning mathematically demanding DSP concepts. AI-supported visualizations can help students observe how changes in time-domain signals affect frequency-domain representations. Simulation tools can also allow them to test filters, examine noise, and compare algorithmic performance. Teachers' lived experiences with classroom AI indicate that these tools can support educational innovation but also raise concerns regarding accuracy, ethics, dependence, and the changing role of the instructor (Rehmat, Hassan, Khan, & Abrar, 2025). Students may accept AI-generated explanations without verifying their mathematical accuracy, or they may use generated code without understanding its operations. Responsible integration therefore requires students to evaluate AI outputs, explain the mathematical logic involved, and validate results through independent analysis. Ethical AI use can affect students' learning patterns, particularly when tools are used to generate answers or complete academic tasks (Ahmed, Urooj, et al., 2025). In DSP education, instructors must design activities that use AI as a scaffold for mathematical reasoning rather than as a substitute for it. Students should be required to interpret results, justify algorithm selection, test generated code, and identify errors or limitations.

Explainable AI may also have educational value because it emphasizes transparency and human understanding of automated decisions. Research on users' perceptions of explainable AI demonstrates the importance of clarity, interpretability, and trust when individuals interact with automated systems (Malik et al., 2026). Human-centered explainable AI research similarly highlights the need to make complex technological outputs understandable to non-specialist users (Rehmat, Hassan, Rumaan, Baig, & Abrar, 2025). Although these studies are not specifically concerned with DSP education, they support the broader argument that students should understand rather than merely accept the outputs of advanced computational tools.

The integration of AI also requires leadership, institutional policy, and faculty development. Research on AI and educational leadership indicates that institutional decision-makers influence how AI is introduced, governed, and supported within educational settings (Kausar & Ahmed, 2026). Without clear pedagogical objectives and staff training, AI adoption may remain superficial and may fail to strengthen students' mathematical readiness.

2.5 Hands-on Learning in DSP Education

Hands-on learning provides an essential link between mathematical theory and real-time DSP implementation. Through practical activities, students can observe how mathematical models behave when applied to actual or simulated signals. They can also learn how sampling, noise, quantization, limited memory, computational delay, and hardware constraints affect system performance. Effective practical learning may include MATLAB, Simulink, Python, digital oscilloscopes, microcontrollers, FPGA platforms, DSP processors, sensor systems, and real-time data-acquisition tools. Students can begin with guided simulations and gradually progress toward open-ended projects involving code optimization and hardware implementation. This progression supports the transfer of mathematical knowledge

from controlled exercises to more complex engineering problems.

DSP applications in telecommunications demonstrate that theoretical algorithms must be evaluated in relation to transmission conditions, noise, bandwidth, and computational requirements (Sadeghi, 2025). Cyber-physical systems similarly require students to understand how computational decisions interact with physical devices and processes (Khalid, 2025). Practical activities are therefore not optional additions to DSP education; they are central to developing implementation readiness. The broader applied-technology literature also shows that emerging technical problems frequently require the integration of theoretical understanding with practical design and implementation (Botto-Tobar et al., 2025). Although not all applied-technology studies focus directly on DSP education, they demonstrate the increasingly interdisciplinary and application-oriented nature of contemporary technical work. Adjacent workplace studies also suggest that access to digital technologies does not automatically produce effective professional performance. The usefulness of digital tools depends on training, organizational support, and employees' ability to integrate them into their work practices (Hanif et al., 2026). Similarly, research on changing work environments indicates that professional readiness involves adaptation, communication, self-management, and the ability to operate within technology-mediated settings (Asif et al., 2026). These findings reinforce the need to prepare DSP students for the broader organizational and collaborative conditions of technical employment.

2.6 The Importance of Interdisciplinary Learning and Industry Collaboration

Real-time embedded DSP is inherently interdisciplinary. It draws on mathematics, electrical and electronic engineering, computer science, software engineering, communication systems, control engineering, and data science. Students who study these areas separately may find it difficult to understand how they interact within

a complete DSP system. An interdisciplinary curriculum should demonstrate how a mathematical model becomes an algorithm, how the algorithm is translated into code, how the code interacts with hardware, and how system performance is evaluated. Such integration can help students understand why mathematical decisions matter in practical applications.

Emerging technologies increasingly require professionals to work across disciplinary boundaries involving AI, computation, communication, and cybersecurity (Kumar et al., 2026). Cyber-physical systems also demonstrate how software, communication networks, embedded hardware, and physical processes must operate as integrated systems (Khalid, 2025). DSP education should therefore provide opportunities for students from different technical backgrounds to collaborate on shared projects. Industry-university collaboration can strengthen this interdisciplinary preparation. Industry partners can provide authentic problem statements, datasets, technical mentorship, internships, equipment, and feedback on curriculum relevance. Such collaboration can help students understand how mathematical and technical decisions are made under real operational constraints.

Research on technological transition in Pakistan's IT sector shows that organizations face managerial and cultural challenges when adopting new working methods and technologies (Rehmat, Hassan, Rumaan, & Abrar, 2025). Although this research does not directly investigate DSP education, it illustrates that graduates must be prepared to work within changing technological and organizational environments. Industry engagement can therefore help universities develop students' technical competence alongside adaptability, teamwork, and professional communication.

2.7 Gaps in Existing Research

Several gaps emerge from the reviewed literature. First, existing DSP literature explains algorithms and technological applications but gives

comparatively limited attention to how students perceive their mathematical readiness for real-time implementation. Reviews of DSP algorithms provide valuable technical knowledge but do not necessarily explain why students struggle to transfer mathematical concepts into practical systems (Sadeghi, 2025). Second, research on AI in education mainly examines general teaching and learning, ethical concerns, teacher confidence, leadership, or user perceptions. It rarely investigates how AI can support the learning of specific mathematical concepts required for embedded DSP (Ahmed, Faisal, et al., 2025; Kausar & Ahmed, 2026). There is also limited evidence on whether AI improves students' independent mathematical reasoning or merely makes solutions more accessible.

Third, studies of technology integration in Pakistan provide important insights into pedagogy and institutional readiness but do not focus specifically on mathematical preparedness for DSP careers (Khan et al., 2025). Other qualitative studies conducted in Pakistan have examined health programmes, workplace conditions, finance, and technology adoption rather than embedded DSP education (Zeb et al., 2025). Consequently, they provide contextual or methodological insights but cannot substitute for direct research on DSP students. Fourth, the literature lacks focused comparative research examining how students in Pakistan and the UK experience the transition from mathematical theory to real-time DSP implementation. Broad assumptions about differences in national resources are insufficient. Comparative qualitative evidence is needed to identify shared experiences, contextual differences, and the educational conditions that influence students' perceived readiness.

Finally, there is insufficient research integrating transfer of learning, situated learning, AI-supported education, interdisciplinary teaching, and industry collaboration within a single account of mathematical readiness for DSP. The present study addresses these gaps by exploring how participating students in Pakistan and the UK

perceive their mathematical preparation, practical learning opportunities, technological support, and readiness for real-time embedded DSP roles.

3. Methodology

This study employed a qualitative comparative design to explore perceived gaps in mathematical readiness for real-time embedded Digital Signal Processing (DSP) roles among university students in Pakistan and the United Kingdom. A qualitative approach was selected because it enabled an in-depth examination of participants' educational experiences, mathematical challenges, practical exposure, and perceived preparation for industry roles.

3.1 Research Design

The study followed a phenomenologically informed approach that focused on how participants understood and interpreted their lived educational experiences. This approach was appropriate because the study examined perceived rather than objectively measured mathematical readiness. Reflexive thematic analysis was used to identify and interpret recurring patterns across the participants' accounts. This method recognized the active role of researchers in interpreting meaning and developing themes from qualitative data (Braun et al., 2022; Byrne, 2022).

3.2 Sampling Strategy

Purposive sampling was used to recruit students with relevant experience of DSP or related technical education. The sample comprised 20 participants, including 10 students from Pakistan and 10 from the UK. Participants had completed at least one year of university education and had studied mathematical concepts relevant to DSP. They represented electrical engineering, electronics engineering, computer engineering, computer science, software engineering, telecommunications engineering, and mechatronics engineering. The balanced sample facilitated comparison between the two groups but was not considered representative of all students in either country.

3.3 Data Collection

Data were collected through semi-structured interviews conducted in person or through video-conferencing platforms, depending on participants' locations. Each interview lasted approximately 45–60 minutes. The interview questions examined participants' mathematical backgrounds, experiences of DSP coursework, difficulties in applying mathematical concepts, practical laboratory exposure, access to DSP tools, use of AI-supported learning, and perceptions of industry readiness. Follow-up questions were used to obtain detailed examples and clarify responses. The interviews were transcribed verbatim for analysis.

3.4 Data Analysis

The interview data were analyzed according to the reflexive thematic-analysis process described by Braun et al. (2022). The researchers first read the transcripts repeatedly to become familiar with the data. Relevant extracts were coded, and related codes were organized into preliminary themes and subthemes. The emerging themes were then reviewed against the complete dataset, refined, defined, and named. Comparative analysis was conducted to identify experiences shared by both groups and those reported more strongly within one context. Representative quotations were

selected to support the interpretations. Participant codes and country affiliations were checked against the profile table to maintain accurate attribution. The analysis remained interpretive and attentive to both dominant patterns and contradictory experiences (Byrne, 2022).

3.5 Ethical Considerations

Participants were informed about the study's purpose, procedures, voluntary nature, and intended use of their responses. Informed consent was obtained before the interviews. Participants were allowed to decline questions or withdraw without penalty. Codes P1–P20 replaced participants' names, and identifying details were removed from the transcripts. Interview records were stored securely, and confidentiality was maintained throughout data collection, analysis, and reporting. Reflexive care was also exercised when interpreting participants' accounts (Hole, 2024).

3.6 Participants' Profile

Participants were between 21 and 25 years old and included 10 males and 10 females. They were enrolled in the second, third, or fourth year of DSP or related programmes. Their academic and demographic characteristics are presented in Table 1.

Table 1: Participant Profiles

Participant	Country	Age	Gender	Academic background	Year of study	DSP or related programme focus
P1	Pakistan	22	Male	Electrical Engineering	Third year	Digital Signal Processing
P2	Pakistan	23	Female	Computer Science	Second year	Embedded Systems
P3	UK	21	Male	Electronics Engineering	Second year	Signal Processing
P4	UK	24	Female	Computer Engineering	Third year	Real-Time Systems
P5	Pakistan	25	Male	Telecommunications Engineering	Fourth year	Real-Time DSP Applications
P6	Pakistan	23	Female	Software Engineering	Third year	Embedded DSP Systems
P7	UK	22	Female	Computer Science	Third year	Signal Processing
P8	UK	21	Male	Electrical Engineering	Second year	Real-Time DSP Systems

Participant	Country	Age	Gender	Academic background	Year of study	DSP or related programme focus
P9	Pakistan	24	Male	Mechatronics Engineering	Third year	DSP and Control Systems
P10	Pakistan	22	Female	Electronics Engineering	Second year	Embedded Systems
P11	UK	23	Female	Electrical and Electronic Engineering	Third year	Digital Signal Processing
P12	UK	22	Male	Computer Engineering	Second year	Real-Time Embedded Systems
P13	Pakistan	24	Female	Computer Science	Third year	DSP in Communication Systems
P14	Pakistan	22	Male	Electrical Engineering	Second year	DSP in Telecommunications
P15	UK	21	Female	Computer Science	Second year	Embedded DSP Systems
P16	UK	24	Male	Electronics Engineering	Third year	Real-Time DSP Applications
P17	Pakistan	25	Male	Computer Engineering	Fourth year	Real-Time Embedded DSP
P18	Pakistan	23	Female	Telecommunications Engineering	Third year	DSP and Communication Systems
P19	UK	22	Male	Electronics Engineering	Second year	Digital Signal Processing
P20	UK	23	Female	Electrical and Electronics Engineering	Third year	Real-Time DSP Systems

4. Findings and Discussion

The reflexive thematic analysis generated five interconnected themes concerning students perceived mathematical readiness for real-time embedded Digital Signal Processing (DSP). The themes addressed mathematical foundations, knowledge transfer, educational support, AI-enabled learning, and alignment with industry expectations. The analysis also identified differences between the Pakistani and UK groups, although these differences were interpreted as patterns within the sample rather than characteristics of the national education systems. The findings indicated that mathematical readiness was not limited to knowledge of formulas or computational procedures. It involved conceptual understanding, numerical reasoning, algorithmic interpretation, software implementation, and the ability to evaluate DSP

performance under real-time constraints. Participants' accounts suggested that mathematics was often taught as an independent theoretical component rather than as an integrated element of signal-processing design and implementation.

4.1 Theme 1: Gaps in Fundamental Mathematical Knowledge

Participants from both countries reported difficulties with mathematical concepts central to DSP, particularly Fourier transforms, calculus, linear algebra, and matrix operations. Their accounts suggested that they had encountered these concepts in university courses but had not always developed a sufficiently deep understanding of their operational significance. The main difficulty was not necessarily the complete absence of mathematical knowledge. Instead, participants appeared to possess

procedural familiarity without consistently demonstrating conceptual or application-oriented understanding. For example, students could perform predetermined mathematical operations but experienced difficulty deciding which method should be applied to an unfamiliar signal-processing problem.

Fourier analysis was perceived as especially challenging because it required students to move between time-domain and frequency-domain representations. Understanding the mathematical expression of a transform did not automatically enable students to interpret spectral components, distinguish signal information from noise, select appropriate sampling parameters, or evaluate the consequences of filtering. Similar difficulties were reported for linear algebra and calculus. Matrix operations were often understood as abstract procedures rather than tools for modelling multidimensional signals, transformations, estimation, and filtering. Calculus was also perceived as disconnected from its role in continuous-time modelling and the analysis of dynamic systems.

These findings showed that students required more than repeated mathematical exercises. They needed contextualized learning activities demonstrating how mathematical structures governed signal behavior and algorithmic performance. This interpretation was consistent with the importance of mathematical reasoning in telecommunications and wireless DSP applications (Sadeghi, 2025).

4.2 Theme 2: Transfer of Mathematical Knowledge to Real-Time DSP

The second theme reflected a pronounced gap between theoretical knowledge and practical implementation. Participants reported that mathematical topics were commonly introduced through lectures, formula-based exercises, and examinations, while practical DSP tasks required programming, simulation, debugging, and system-level interpretation. This gap became more visible when students attempted to move from a mathematically defined problem to an

implementable algorithm. Real-time DSP required students to select an appropriate mathematical method, translate it into computational steps, write or modify code, test the algorithm using signal data, and evaluate whether the implementation satisfied timing and accuracy requirements.

Participants' accounts indicated limited exposure to constraints such as sampling rate, quantization, finite word length, numerical precision, latency, processor capability, memory consumption, and computational complexity. An algorithm could therefore be mathematically valid but unsuitable for an embedded platform because its implementation exceeded the available processing time or hardware resources. This finding supported the transfer-of-learning perspective adopted in the study. Mathematical knowledge acquired through structured classroom exercises had not automatically transferred to unfamiliar engineering problems. It also supported situated learning because students associated stronger understanding with simulations, laboratories, embedded hardware, and project-based activities. Real-time and cyber-physical systems required close interaction among mathematical models, algorithms, software, sensors, processors, and physical processes (Khalid, 2025). Consequently, practical exposure was not an additional component of mathematical readiness; it was an essential condition for transforming mathematical knowledge into deployable DSP competence.

4.3 Theme 3: Educational and Technological Support

The third theme concerned the institutional conditions that influenced students' learning. Participants discussed access to laboratories, DSP software, embedded development platforms, faculty expertise, technical mentoring, and industry-linked projects. These conditions affected the opportunities available for applying mathematical concepts. Pakistani participants generally reported comparatively limited access to specialized DSP laboratories, licensed software, embedded hardware, and faculty members with

recent industry experience. These limitations appeared to reduce opportunities for repeated experimentation and implementation. Students could study DSP concepts theoretically but had fewer opportunities to observe how algorithms performed on real or simulated signals.

UK participants generally reported stronger access to DSP software, laboratory facilities, project-based learning, and faculty members with industry connections. Nevertheless, these participants also experienced difficulties translating mathematical knowledge into real-time applications. The findings therefore indicated that resource availability was important but not sufficient. Effective educational support required purposeful alignment among mathematical courses, DSP modules, laboratory activities, and assessment. Students needed structured progression from mathematical derivation to simulation, software implementation, hardware deployment, and performance evaluation. The interaction between conventional teaching and technology-integrated pedagogy remained important in developing applied competence (Khan et al., 2025).

The comparison suggested that the Pakistani group faced more substantial infrastructural and exposure-related barriers, whereas the UK group experienced a more specific pedagogical transfer problem. However, variations were also evident within each group, preventing simple national-level conclusions.

4.4 Theme 4: AI and Emerging Technologies

The fourth theme concerned the perceived role of artificial intelligence and emerging technologies in strengthening mathematical readiness. Participants associated AI-supported learning with visualization, simulation, personalized explanations, code assistance, and automated feedback. AI tools were considered potentially useful for exploring relationships between time-domain and frequency-domain signals, testing alternative algorithms, identifying coding errors, and observing how parameter changes affected system performance. Such capabilities could make

abstract mathematical concepts more accessible and support iterative experimentation.

However, participants reported that AI had not been systematically integrated into their DSP curricula. Exposure appeared fragmented and was often driven by students' individual use rather than by formally designed learning activities. Pakistani participants generally reported more limited institutional integration, while UK participants described relatively greater access to digital tools without necessarily receiving structured guidance on their mathematical use. The findings also revealed an important risk: AI could generate explanations or code without ensuring that students understood the underlying mathematical reasoning. Consequently, AI-supported education needed to require validation, interpretation, and critical evaluation. Students needed to explain why an algorithm was appropriate, verify the mathematical assumptions, test the generated output, and identify possible errors.

This interpretation was consistent with research highlighting the opportunities and ethical challenges associated with classroom AI integration (Rehmat et al., 2025). It also reflected the importance of transparency and interpretability in automated systems (Malik et al., 2026). AI was therefore interpreted as a potential cognitive and computational support rather than a substitute for mathematical understanding.

4.5 Theme 5: Alignment Between Education and Industry Expectations

The final theme concerned the perceived mismatch between university preparation and the practical requirements of DSP employment. Participants believed that employers expected graduates to apply mathematical concepts, use industry-standard software, implement algorithms, analyze real signals, troubleshoot systems, and operate within real-time computational constraints. Participants' academic preparation was perceived as stronger in theoretical knowledge than in integrated problem-solving. They reported insufficient opportunities

to complete tasks that required the full DSP development cycle: mathematical modelling, algorithm selection, simulation, programming, embedded implementation, testing, optimization, and technical documentation.

The findings also suggested that industry readiness required multidisciplinary competence. Contemporary DSP roles are increasingly intersected with artificial intelligence, embedded computing, communication systems, control engineering, cybersecurity, and data analysis (Kumar et al., 2026). Students therefore needed to understand how mathematical and computational

decisions influenced system reliability, processing speed, accuracy, and resource utilization. The perceived mismatch indicated a need for greater industry–university collaboration. Industry-informed projects, internships, technical mentoring, equipment partnerships, and practitioner participation in curriculum review could expose students to realistic design constraints. However, because industry representatives were not included in the study, these findings represented students’ perceptions of employer expectations rather than independently verified industry requirements.

Table 2: Thematic Analysis of Mathematical Readiness for Real-Time Embedded DSP

Theme	Subtheme	Representative codes	Comparative pattern	Analytical interpretation
Fundamental mathematical knowledge	Conceptual difficulty with core DSP mathematics	Fourier transforms, calculus, linear algebra, matrix operations, signal theory	Reported by both groups	Students possessed varying levels of procedural knowledge but experienced difficulty interpreting mathematical concepts within DSP applications. Classroom knowledge did not transfer automatically to unfamiliar or computationally constrained DSP problems.
Transfer of mathematical knowledge	Disconnect between theoretical learning and implementation	Theory–practice gap, algorithm translation, coding, simulation, interpretation	Strongly reported in both groups	Students had insufficient opportunities to evaluate mathematically valid algorithms under embedded-system constraints.
Transfer of mathematical knowledge	Limited experience with real-time constraints	Sampling, quantization, latency, memory, numerical precision, computational complexity	Reported across both contexts	Institutional resources influenced opportunities for experimentation, but access alone did not guarantee applied competence.
Educational and technological support	Access to tools, laboratories, and technical guidance	DSP software, embedded hardware, laboratories, faculty expertise, technical mentoring	Resource limitations were more prominent among Pakistani participants	Industry engagement supported contextual learning, although the theory–practice gap remained present.
Educational and technological support	Industry-informed learning	Internships, practical projects, faculty industry exposure, curriculum relevance	UK participants generally reported stronger institutional and	

Theme	Subtheme	Representative codes	Comparative pattern	Analytical interpretation
			industry connections	
AI and emerging technologies	AI-supported mathematical learning	Visualization, simulation, adaptive explanation, coding assistance, feedback	Both groups recognized potential benefits; structured access varied	AI could scaffold mathematical understanding when students were required to interpret and verify its outputs.
AI and emerging technologies	Limited and unstructured curriculum integration	Informal AI use, curriculum gaps, ethical concerns, overdependence	More limited institutional integration was reported in Pakistan	AI use remained fragmented and required pedagogical structure, validation, and ethical guidance.
Education-industry alignment	Perceived demand for implementation competence	Industry-standard tools, problem-solving, debugging, optimization, real-time deployment	Reported by both groups	Students perceived that employers expected integrated mathematical, computational, and engineering competence.
Education-industry alignment	Insufficient authentic preparation	Practical training, capstone projects, internships, multidisciplinary work	Shared concern across the two groups	Curricula provided insufficient exposure to the complete DSP development and deployment cycle.

4.6 Discussion

The findings indicate that students in both Pakistan and the United Kingdom possessed basic mathematical knowledge but experienced difficulty applying concepts such as Fourier transforms, calculus, and linear algebra to real-time embedded DSP problems. This finding supports the transfer-of-learning perspective, which explains that knowledge acquired in one context does not automatically transfer to unfamiliar practical situations (Barnett & Ceci, 2002). It also aligns with Situated Learning Theory, which emphasizes that competence develops through participation in authentic activities involving real tools, problems, and professional contexts (Lave & Wenger, 1991). Participants associated stronger understanding with simulation, programming, laboratory work, embedded hardware, and project-based learning. This observation is consistent with Sadeghi

(2025), who highlighted the importance of connecting DSP algorithms with their practical applications in communication systems. Although UK participants generally reported better access to laboratories, software, and industry-linked learning, they continued to experience difficulties converting mathematical theory into workable algorithms. This suggests that resources alone cannot ensure practical competence without purposeful curriculum integration. Participants also considered AI useful for visualization, coding assistance, simulation, and feedback. However, concerns about inaccurate outputs, dependence, and limited understanding support earlier research emphasizing the need for ethical guidance, verification, and structured pedagogical integration of AI tools (Rehmat et al., 2025; Malik et al., 2026).

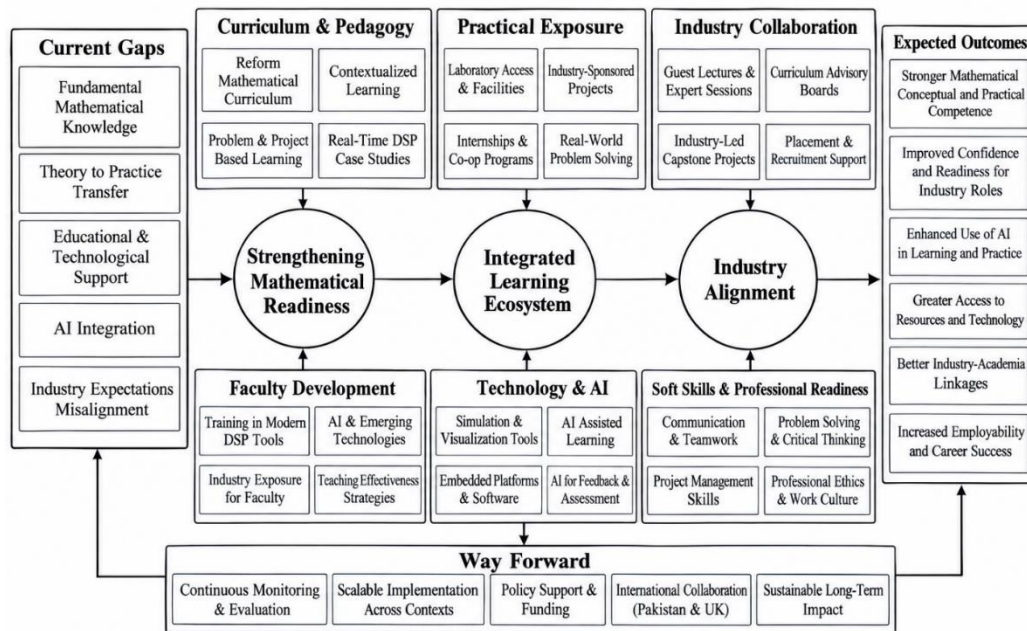


Figure 1. Proposed Action Plan for Strengthening Mathematical Readiness and Industry-Oriented Competence in Real-Time Embedded DSP

5. Conclusion, Implications, Limitations and Directions for Future Research

5.1 Conclusion

This study explored students' perceived mathematical readiness for real-time embedded Digital Signal Processing (DSP) roles in selected educational contexts in Pakistan and the United Kingdom. The analysis showed that mathematical readiness extended beyond familiarity with Fourier transforms, calculus, linear algebra, and signal-processing theory. It also involved the ability to translate mathematical relationships into algorithms, simulations, executable code, and embedded implementations operating under practical constraints. Participants from both groups reported difficulty transferring classroom knowledge to real-time DSP problems. Their accounts indicated that formula-based instruction and conventional assessment had not always provided sufficient preparation for algorithm selection, numerical interpretation, programming, debugging, hardware deployment, or performance

evaluation. Limitations in exposure to sampling effects, quantization, finite-word-length behavior, latency, memory use, and computational complexity further restricted their perceived implementation readiness.

Differences also emerged between the two contexts. Pakistani participants generally reported more substantial limitations in access to specialized laboratories, industry-standard software, embedded platforms, and industry-informed academic support. UK participants described comparatively stronger technological resources and industry connections. Nevertheless, they also experienced difficulty converting mathematical understanding into deployable DSP solutions. The findings therefore indicated that infrastructure was important, but access to technology alone did not ensure mathematical transfer or implementation competence. AI and emerging technologies were perceived as potentially useful for visualization, simulation, code development, and automated feedback. However, their integration into DSP education

appeared fragmented rather than pedagogically structured. The study concluded that AI could support mathematical learning only when students were required to explain mathematical assumptions, verify generated outputs, assess numerical validity, and evaluate implementation performance. AI was therefore better understood as a learning scaffold than as a replacement for mathematical reasoning.

Overall, the study concluded that improved DSP readiness required closer alignment among mathematics instruction, signal-processing theory, programming, laboratory work, embedded implementation, assessment, and industry engagement. Students needed progressively structured opportunities to move from mathematical derivation to simulation, coding, hardware deployment, testing, and optimization.

5.2 Theoretical Implications

The findings extended the transfer-of-learning perspective by showing that mathematical knowledge acquired through structured classroom exercises had not automatically transferred to complex DSP tasks. Participants' difficulties became more evident when problems required them to select mathematical methods independently, translate equations into computational operations, and work within real-time system constraints. This indicated that the distance between the learning context and the application context influenced the successful transfer of mathematical knowledge. The findings also supported the situated-learning perspective. Students associated stronger preparation with authentic tools, realistic datasets, laboratory activities, embedded hardware, practical projects, and industry engagement. Mathematical readiness therefore developed through participation in technically meaningful activities rather than through abstract instruction alone. Real-time DSP competence required interaction among mathematical models, algorithms, processors, software, sensors, and physical processes, reflecting the wider structure of cyber-physical systems (Khalid, 2025).

The study further conceptualized mathematical readiness as a multidimensional capability comprising conceptual understanding, procedural fluency, computational translation, numerical judgement, and implementation awareness. This interpretation extended beyond conventional definitions based primarily on examination performance. It also reinforced the interdisciplinary character of DSP, which increasingly connected mathematics with engineering, artificial intelligence, computation, communication, and cybersecurity (Kumar et al., 2026). The findings concerning AI supported research showing that educational technologies created opportunities for interactive learning while introducing concerns about accuracy, ethics, dependence, and pedagogical integration (Rehmat et al., 2025). Institutional leadership and faculty readiness remained important in determining whether AI was integrated meaningfully into technical education (Kausar & Ahmed, 2026). The study therefore positioned AI-supported DSP learning within a broader system of curriculum design, faculty capability, assessment, and responsible technology use.

5.3 Practical Recommendations

Universities should redesign DSP learning activities so that mathematical concepts are progressively connected with implementation. Fourier analysis, linear algebra, calculus, probability, and numerical methods should be taught through signal-processing examples rather than as isolated mathematical topics. Students should be required to interpret results, justify method selection, and explain how mathematical decisions influence signal quality and system behavior. DSP laboratory work should progress from guided simulations to open-ended implementation. Students could initially model filters and transformations in MATLAB or Python before transferring selected algorithms to microcontrollers, DSP processors, or FPGA platforms. Laboratory activities should examine sampling, aliasing, quantization, numerical precision, latency, memory consumption, and

computational cost. Such progression would help students understand why a mathematically valid algorithm might not be deployable on a resource-constrained embedded platform.

Assessment should also evaluate integrated competence. In addition to solving mathematical problems, students should design algorithms, analyze real signals, debug code, compare alternative implementations, and evaluate performance against defined real-time requirements. Capstone projects should reflect the complete DSP development cycle, including mathematical modelling, simulation, implementation, validation, optimization, and technical documentation. Universities should strengthen collaboration with DSP-related industries through internships, practitioner-led workshops, curriculum consultation, technical mentoring, equipment partnerships, and industry-defined projects. These activities could expose students to authentic engineering constraints and clarify the competencies expected in professional roles. Because the present study examined only students' perceptions, future curriculum revisions should also incorporate direct input from employers and practicing DSP engineers.

AI tools should be incorporated through structured activities rather than informal use. Students could use AI to visualize signals, compare algorithms, identify programming errors, and generate alternative solutions. However, they should be required to verify all outputs, explain the underlying mathematics, test generated code, and identify limitations. This approach would promote responsible use and reduce the risk of substituting automated responses for independent reasoning. Faculty development should address modern DSP software, embedded platforms, AI-supported teaching, project supervision, and current industry practices. This requirement appeared particularly important in settings where participants reported limited access to industry-oriented academic support. Technology-integrated pedagogy depended on both infrastructure and instructors' ability to connect tools with meaningful learning objectives (Khan et al., 2025).

5.4 Limitations

The study had several limitations. Its purposive sample consisted of 20 students from selected educational contexts, and the findings could not be treated as representative of all DSP students in Pakistan or the UK. The balanced country distribution facilitated comparison, but it did not justify generalizations about either national education system. The findings should therefore be interpreted in relation to the participants and programmes included in the study. The study investigated perceived rather than objectively demonstrated mathematical readiness. Participants' descriptions of their strengths and difficulties might not have corresponded directly with their actual performance. Self-reported data could also have been influenced by memory, confidence, social desirability, or differences in participants' expectations.

Participants represented different academic disciplines and years of study. Consequently, their exposure to mathematics, DSP theory, programming, hardware, and practical projects was unlikely to have been identical. Although this diversity broadened the range of experiences, it limited direct equivalence across participants. The study also excluded faculty members, curriculum designers, laboratory instructors, employers, and practicing DSP engineers. Statements concerning industry expectations therefore represented students' perceptions rather than verified professional competency requirements. Furthermore, the study did not evaluate the effectiveness of particular teaching methods, AI platforms, laboratory interventions, or industry partnerships.

5.5 Future Research Directions

Future research should include larger and more diverse samples drawn from multiple institutions in Pakistan and the UK. Comparative studies could examine differences across university types, engineering disciplines, academic levels, and levels of laboratory infrastructure. Greater contextual detail would improve the transferability of findings without assuming national uniformity. A

mixed-methods design could combine interviews with objective assessments of mathematical reasoning, DSP programming, signal interpretation, and embedded implementation. Performance-based tasks could determine whether perceived readiness corresponded with demonstrated competence. Longitudinal research could also track how mathematical and practical readiness developed across successive years of study.

Future studies should incorporate the perspectives of faculty members, curriculum designers, employers, and DSP professionals. Comparing these perspectives with students' accounts would provide a more complete understanding of curriculum-industry alignment and reveal whether perceived skill gaps matched actual workplace requirements. Experimental or quasi-experimental studies could evaluate specific educational interventions, including AI-supported visualization, simulation-based learning, hardware laboratories, industry-designed capstone projects, and integrated mathematics-DSP modules. Their effectiveness could be assessed through conceptual understanding, implementation, accuracy, computational efficiency, confidence, and retention.

Further research should also examine how AI affected independent reasoning. Particular attention should be given to whether AI-supported tools improved conceptual understanding or merely accelerated answer generation. Research in this area should evaluate mathematical accuracy, explainability, ethical use, and students' ability to verify computational outputs.

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