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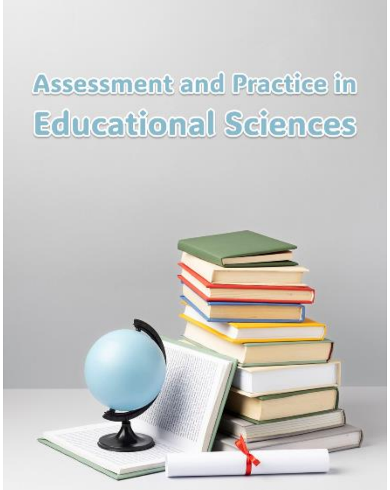

Cognitive Competency-Based Technical and Engineering Education: A Systematic Review

ABSTRACT

This systematic review aimed to identify, appraise, and synthesize prior research on cognitive competency-based technical and engineering education. A systematic search based on PRISMA was conducted across reputable scientific databases, including Web of Science, Scopus, IEEE Xplore, Google Scholar, Science Direct, and the Iranian database Noormags. Following the screening of 320 identified records, 15 studies meeting the inclusion criteria were selected for analysis. The findings indicate that cognitive competencies in engineering education are not a set of discrete and separable abilities, but rather an integrated and mutually constitutive network. Critical thinking, problem solving, working memory, cognitive flexibility, self-regulation, and emotion regulation are deployed simultaneously and in an intertwined manner in authentic professional situations, and their analytical separation yields a reductive account of engineering cognition. The present review further demonstrates that cognitive processes constitute the foundation of learning, and without them, deep, durable, and transferable learning does not take shape. Neglect of these processes results in the training of graduates with strong theoretical knowledge but limited applied capacity, particularly in complex and uncertainty-laden situations that necessitate the management of cognitive resources and decision-making under ambiguity. The present analysis also reveals that cognitive competencies are dynamic and context-bound in nature, taking shape through the interaction among the individual, the task, and the context; their assessment and cultivation therefore require a process-oriented, multi-wave, and context-sensitive approach. It is concluded that embedding agency, self-regulation, and cognitive competencies within the explicit objectives of the curriculum is not optional but imperative for enhancing the quality of engineering education and graduates' employability. The realization of this aim requires a holistic curricular architecture rather than an additive treatment of skills, so that the link between theoretical knowledge and practical application may be established.

Keywords: competency, cognitive competency, technical and engineering students, engineering students, engineering education, problem-based learning

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Introduction

Engineering education occupies a strategic position in contemporary higher education because engineers are expected not only to master specialized scientific and technical knowledge but also to respond effectively to rapidly changing technological, economic, environmental, and social conditions. The acceleration of digital transformation, artificial intelligence, automation, Industry 4.0, sustainability imperatives, and globalization has substantially altered both the nature of engineering work and the competencies required for successful professional performance. Consequently, the traditional conception of engineering education as primarily the transmission of disciplinary knowledge and technical procedures is increasingly inadequate. Contemporary engineering graduates are expected to learn continuously, adapt to novel technologies, manage complex information, collaborate across disciplinary and cultural boundaries, and make reasoned decisions under uncertainty. These expectations have encouraged a transition from content-centered curricula toward competency-based, experiential, and learner-centered educational models that connect theoretical learning to authentic professional challenges (1-4). This transformation has become particularly important because educational systems are increasingly evaluated not merely by the knowledge they transmit but by their capacity to prepare graduates for meaningful participation in economies and societies characterized by continuous technological and organizational change.

This changing educational landscape has also strengthened interest in the concept of competency. Although competency has long been employed in vocational education, human-resource development, and professional training, its meaning remains multidimensional and, at times, conceptually ambiguous. Early conceptualizations emphasized the integration of knowledge, skills, attitudes, and personal attributes required for effective performance rather than the possession of knowledge alone (5, 6). Competency models subsequently developed toward increasingly holistic formulations in which successful performance depends on the coordinated mobilization of multiple personal resources in response to situational demands (7, 8). Knowledge, skills, and abilities may therefore be analytically distinguished, yet competence emerges through their functional integration when individuals confront authentic tasks (9). This contextual interpretation is particularly important in higher education because competencies cannot be treated as fixed attributes that operate independently of educational, occupational, and institutional environments. Employability itself has increasingly been understood as a developmental and context-sensitive phenomenon shaped by interactions between individual resources and surrounding opportunities (10).

Within engineering education, this broader understanding of competency has generated growing concern regarding the balance between technical expertise and transferable capabilities. Employers and educational institutions have repeatedly identified communication, teamwork, problem solving, self-management, adaptability, critical thinking, and responsibility as important dimensions of graduate readiness (11, 12). The continuing debate over whether higher education adequately prepares graduates for employment demonstrates that disciplinary expertise, although indispensable, does not by itself guarantee effective workplace performance (13). Contemporary reviews of global employability skills likewise indicate that workplaces increasingly value combinations of cognitive, interpersonal, technological, and adaptive capacities rather than narrow occupational knowledge (14). In engineering-related professional contexts, this demand becomes particularly significant because graduates frequently confront poorly structured problems for which no predetermined technical procedure provides a complete solution. Accordingly, identifying the competencies that enable engineering students to transform technical knowledge into effective professional action constitutes a central educational challenge.

Engineering competency also has an important professional-identity dimension. Students do not become engineers solely by acquiring disciplinary content; they gradually develop understandings of what competent professional practice means, how professionals behave, and how they themselves belong within a professional community. Studies of professional identity formation emphasize that competence, recognition, belonging, responsibility, and engagement with professional norms interact throughout the process by which learners come to perceive themselves as legitimate members of a profession (15, 16). Research examining the relationship between competency-based education and professional identity further suggests that observable competence and identity development should not be treated as competing objectives, because professional action reflects both what individuals can do and how they understand their professional roles (17). Similar observations in other professional disciplines demonstrate that identity formation is a developmental process shaped by education, practice, interpersonal interaction, and participation in professional settings (18). Civic and social identities further underline that professional education involves participation, values, and responsibility in addition to technical expertise (19).

These issues are directly relevant to engineering, where collaborative practice has become increasingly important. Engineering projects are commonly undertaken through multidisciplinary teams, and globalization has expanded the importance of cross-cultural collaboration, communication, role negotiation, and coordination (20). Engineering students therefore require more than the capacity to execute individual technical tasks. Their preparation must also enable them to work productively with others, manage disagreements, assume appropriate responsibilities, and respond constructively when team performance becomes uneven (21). Faculty perceptions of engineering leadership preparation similarly indicate that professional readiness includes interpersonal and leadership competencies alongside conventional technical capacities (22). Educational approaches that combine cooperative activity with active pedagogies can facilitate the development of such soft skills, particularly when students are required to participate, communicate, make decisions, and share responsibility for learning outcomes (23). Apprenticeship and practice-oriented education provide another route through which competencies can be connected to professional growth by placing students in contexts where knowledge must be mobilized in relation to actual occupational demands (24).

Nevertheless, the competencies underlying successful professional performance are not exclusively social or behavioral. Cognitive competencies form a fundamental substrate through which learners understand information, analyze relationships, generate alternatives, solve problems, regulate their actions, and transfer learning from one context to another. A systematic perspective on student cognitive competencies suggests that these capacities affect not only academic learning but also self-efficacy, adaptive functioning, decision-making, and students' ability to deal with emerging educational challenges (25). Evidence concerning academic achievement likewise points to the importance of cognitive ability as a foundation of effective learning performance (26). At the same time, balanced development appears to require interaction between cognitive and non-cognitive competencies rather than reliance on either category in isolation (27). Thus, cognitive competency should not be reduced to intelligence or isolated information-processing ability; instead, it encompasses interconnected processes through which learners regulate, interpret, evaluate, and apply knowledge in demanding situations.

Critical thinking is particularly prominent within this domain because engineering problems often require the evaluation of competing evidence, assumptions, constraints, and potential solutions. Studies using engineering design processes demonstrate that engagement with authentic design problems can stimulate students' reasoning, hypothesis evaluation, analytical judgment, and critical thinking, while stronger critical thinking simultaneously contributes to more sophisticated engineering problem solving (28). Research involving engineering students has also linked critical thinking to more effective management of academic challenges and lower levels of problematic academic behaviors such as procrastination and burnout (29). Despite its recognized importance, however, assessment practices remain heterogeneous, and comprehensive evaluation of critical thinking in engineering education remains methodologically challenging (30). These findings indicate that cognitive competency development requires more than declaring critical thinking to be a curricular objective; educational systems must clarify what its components are, how they interact with other cognitive processes, and how they can be reliably developed and assessed.

Problem solving, self-regulation, cognitive flexibility, and the management of learning processes are equally important. Engineering students differ substantially in how they regulate their learning, select strategies, monitor progress, and adapt their approaches when initial strategies prove ineffective (31). Interventions designed to help engineering students become more effective learners further suggest that learners' action regulation and their capacity to translate intentions into effective study behavior can be educationally influenced (32). The importance of these processes becomes clearer when engineering is understood as a profession requiring sustained engagement with complex and changing tasks. Technical knowledge cannot produce optimal performance when students are unable to allocate cognitive resources, monitor errors, persist through difficulty, or revise ineffective approaches. Hence, self-regulated learning and related cognitive mechanisms should be regarded as constitutive elements of engineering competency rather than supplementary study skills.

Digital transformation adds another layer to this challenge. Industry 4.0 has intensified the need for competencies related to complex data, human–machine collaboration, lifelong learning, and adaptive use of intelligent technologies, encouraging engineering education to integrate cognitive technologies and smart learning environments into curriculum design (33). More recently, generative artificial intelligence has introduced new opportunities and demands, requiring engineering students to develop the ability to use AI tools while critically evaluating their outputs and understanding their role within disciplinary learning and professional practice (34). Artificial intelligence is also beginning to influence competency assessment itself. AI-supported systems such as competency-oriented rubric platforms demonstrate the potential to map, assess, and support competency development more systematically, although technological sophistication cannot substitute for a coherent conceptual definition of the competencies being assessed (35). The digital age therefore makes conceptual clarity regarding cognitive competencies more urgent rather than less important.

Technology-enhanced learning can support competency development when it is embedded within appropriate pedagogy. The Community of Inquiry perspective in engineering e-learning emphasizes the interaction of cognitive, teaching, and social dimensions in creating meaningful educational experiences (36). Educational technologies have likewise been used to support competency acquisition in engineering courses dealing with interdisciplinary challenges such as biomimetics and sustainability (37). Project-based approaches, including robotics-centered engineering activities, offer students opportunities to integrate conceptual understanding with designing, constructing, testing, collaborating, and problem solving (1). Challenge-based educational models similarly organize learning around authentic problems that require students to integrate knowledge from multiple domains rather than reproduce information in isolation (38). Such approaches suggest that cognitive competencies are cultivated most effectively when students are repeatedly required to mobilize them during meaningful activity.

Sustainability provides another example of why engineering education must move beyond narrow technical rationality. Engineering decisions increasingly involve environmental, social, economic, and ethical trade-offs, requiring students to recognize complex consequences rather than optimize a single technical parameter. Cognitive and neurocognitive research indicates that the framing of engineering problems can influence attention, judgment, empathy, and decisions related to sustainable alternatives (39). At the institutional level, however, the integration of sustainable development within engineering education may be constrained by traditional pedagogical practices, fragmented curricula, insufficient infrastructure, resistance to innovation, and limited faculty preparation (3). Education for the digital age and sustainable development therefore requires competencies that allow learners to adapt knowledge, reason across interconnected systems, and continue learning as technological and societal expectations evolve (40).

The importance of context is also visible within specific engineering disciplines. Research on architectural graduates has demonstrated the significance of identifying professional competencies according to the actual requirements of professional practice rather than relying exclusively on university-based assumptions regarding graduate preparation (41). In railway engineering education, learning outcomes have similarly been associated with factors such as students' familiarity and satisfaction with their field, study habits, instructional approaches, practical learning opportunities, facilities, and the broader educational environment (42). These findings reinforce the proposition that competency development emerges from interactions among learner characteristics, teaching processes, curriculum structure, and environmental opportunities. The growing international mobility of STEM students adds another contextual dimension, since engineering education increasingly takes place within transnational knowledge spaces in which students' aspirations and learning trajectories are shaped by perceived educational and professional opportunities across countries (43). Competency models that disregard these contextual differences risk treating engineering students as a homogeneous population and overlooking important variations in how competencies emerge and are enacted.

A further problem concerns the relationship between engineering education and the labor market. The ultimate value of competency-based education cannot be reduced to immediate employment, yet employability remains an important criterion through which the relevance of higher education is judged. Studies of successful graduates have long demonstrated the potential value of using graduate experiences to identify educational attributes associated with effective transition into professional practice (44). At the same time, contemporary employability research warns against conceptualizing graduate outcomes as the simple product of individual skills, because employability is shaped by institutional, occupational, and contextual conditions (10). Broader educational and economic perspectives similarly connect lifelong learning, inclusion, investment in education, and human-capital development with economic growth, underscoring the wider societal implications of educational quality (4). Engineering education must therefore prepare students simultaneously for immediate professional participation and for continuous competency renewal throughout changing careers.

Taken together, the literature demonstrates considerable progress in identifying individual competencies relevant to engineering education, including critical thinking, problem solving, teamwork, communication, self-regulated learning, technological competence, sustainability-oriented reasoning, professional identity, and adaptability. Yet this expanding literature also reveals a conceptual fragmentation. Different studies frequently isolate particular skills, examine them through different theoretical traditions, or classify similar characteristics under cognitive, non-cognitive, professional, employability, or soft-skill categories. Such fragmentation makes it difficult to determine which competencies are genuinely cognitive in nature, how different cognitive components relate to one another, and how they jointly support learning and professional performance. The increasing diversity of educational models, emerging technologies, professional expectations, and assessment systems further amplifies the need for an integrated conceptual framework capable of organizing the cognitive foundations of engineering learning and practice.

Accordingly, a systematic synthesis is necessary because cognitive competencies should not be understood as a checklist of independent abilities added to an otherwise unchanged technical curriculum. Contemporary evidence instead suggests that effective engineering performance emerges through interactions among analytical reasoning, problem solving, cognitive flexibility, self-regulation, decision-making, learning strategies, and contextual demands. Competency-based engineering education therefore requires a coherent account of how these capacities are defined, cultivated, assessed, and integrated with technical and professional learning. Such an account is particularly important for reducing the persistent divide between theoretical mastery and practical performance and for supporting graduates who can function effectively in complex, technology-intensive, uncertain, collaborative, and continuously changing professional environments.

Therefore, the aim of the present study was to systematically identify, appraise, and synthesize the existing evidence on cognitive competency-based technical and engineering education in order to clarify the principal cognitive competencies, their characteristics, and their role in the learning and professional development of technical-engineering students.

Methods and Materials

The present study was a systematic review conducted with the aim of identifying, appraising, and synthesizing the findings of prior research on cognitive-competency-based technical-engineering education. This method was selected in order to provide a comprehensive and structured perspective on competency-based education and its emphasis on cognitive stances. To retrieve relevant articles, a systematic search based on PRISMA was conducted in reputable scientific databases, including Web of Science, Scopus, IEEE Xplore, Google Scholar, and Science Direct, as well as the Iranian database Noormags.

The search strategy was designed based on combining primary and overlapping keywords in two domains: cognitive competencies (e.g., critical thinking, problem solving, working memory, cognitive flexibility) and technical-engineering education (e.g., engineering education, technical-vocational education, problem-based learning, technical-engineering students). The inclusion criteria were a direct connection with cognitive processes and learning in technical-engineering settings, publication within the period 2010–2016, and classification as original research or review articles; articles in Persian or English were also included. Duplicate articles, articles with a purely cognitive focus that paid no attention to engineering education, conference papers, and articles lacking research-scientific standing were excluded from the review cycle.

The article-selection and extraction process proceeded in three stages. The first stage, initial screening, examined the titles and abstracts of the retrieved articles to remove irrelevant items; the second stage, full-text appraisal, involved reading the full texts of the remaining articles to ensure conformity with the research objectives; and the final stage consisted of extracting key data, including author details, year of publication, type of educational approach, cognitive competencies, and main findings.

Following the final selection of articles, the extracted data were analyzed using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) reporting framework. In total, 320 articles were identified; after the screening stages and the removal of irrelevant titles, those articles related to technical-engineering education and cognitive characteristics—approximately 90 articles—were selected. After examining the abstracts in the final stage, 15 articles were chosen that met the criteria for analysis and provided suitable information for synthesis and for the derivation of a systematic model.

Findings and Results

The reviewed studies consistently showed that cognitive competencies constitute a central foundation of effective engineering education and are closely associated with academic achievement, learning quality, and professional adaptability. Alarcon-Pereira et al. (2026) emphasized that institutional, structural, mental, and cultural barriers—such as fragmented educational policies, traditional teaching methods, resistance to innovation, inadequate infrastructure, and limited faculty awareness—can obstruct the development of sustainable engineering education, while cognitive and attitudinal maturity among both students and faculty can facilitate educational transformation. Similarly, Hoang and Nguyen (2026) argued for a transition from content-driven curricula toward competency-based and experiential education, indicating that appropriate instructional design can improve educational quality even under resource constraints. Soufi et al. (2025) reported that strengthening cognitive competencies can improve learning strategies, cognitive development, mental health, self-efficacy, and decision-making, particularly in an educational environment increasingly influenced by artificial intelligence. Armijo (2025) likewise demonstrated the importance of both cognitive and non-cognitive competencies for academic achievement and individual performance, while also highlighting disagreement over whether cognitive competency should be viewed as a collection of separate attributes or as an integrated configuration of mutually reinforcing abilities. Consistent with this perspective, Gemma and Mjokaya (2024) identified cognitive competencies as a basis for academic performance, psychological well-being, and long-term professional adaptability. AlDhaen (2023) further showed that certain cognitive skills, particularly symbolization, numerical calculation, and numerical comprehension, develop significantly during engineering education, although spatial visualization may remain relatively stable, with age contributing to cognitive development while gender exerts no substantial effect.

A second major group of findings concerned critical thinking, problem solving, decision-making, and the instructional conditions through which these competencies can be cultivated. Deo et al. (2023) found that assessment of critical thinking in engineering education remains inconsistent, with relatively few instruments comprehensively covering all dimensions of the construct, indicating an important weakness in current assessment practices. Purwandari et al. (2022) showed that engineering education can strengthen decision-making, problem-solving, and critical-thinking abilities when cognitive, pedagogical, and social interactions are effectively integrated, while such interactions can also improve motivation and collaborative engagement. Putra et al. (2021) similarly identified a reciprocal relationship between engineering design and critical thinking: critical thinking enhances engineering design, while engagement in engineering design strengthens reasoning, hypothesis generation and evaluation, and analytical problem solving. Tahmasebzadeh Sheikhlar et al. (2021) further demonstrated that critical thinking plays a protective role in relation to academic burnout and procrastination, whereas entrepreneurial spirit and motivation alone are insufficient to address these problems. At the instructional and environmental level, Mosayebi et al. (2025) identified satisfaction with and familiarity with the field, practical learning, educational facilities and environment, study habits, teaching methods, and educational quality as major influences on engineering students' learning outcomes. Vahdat Ghasemi et al. (2024) additionally found that functional competencies received the highest priority in relation to the employability of architecture graduates, while social competencies received the lowest ranking from students.

The remaining studies highlighted the growing influence of digital transformation, sustainability, globalization, and emerging professional expectations on engineering competencies. Mingaleva and Vukovic (2020) reported that cognitive technologies enhance conceptual understanding and problem-solving abilities and that digital and intelligent learning environments support personalized and self-regulated learning. They further identified lifelong learning, human-machine collaboration, and the ability to manage complex data as essential competencies in Industry 4.0, suggesting that engineering education should increasingly integrate smart and cognitive learning technologies. Hu and Shealy (2022) demonstrated that cognitive and neurocognitive preparation can improve engineers' decision-making and encourage the selection of more sustainable alternatives, while also strengthening analytical thinking and empathy. Their findings indicate that engineering decisions are shaped not only by technical logic but also by cognitive and emotional factors, thereby supporting educational approaches that address mindset and attitude as well as technical knowledge. Finally, Zhang (2024) emphasized that rapid technological development and globalization have transformed engineering education from a predominantly knowledge-based model toward a competency-development model. This transformation requires engineers to possess communication abilities, flexible professional roles, and the capacity to collaborate effectively in multidisciplinary and multicultural teams. Taken together, the reviewed evidence indicates that contemporary engineering education increasingly depends on an integrated set of cognitive, functional, technological, collaborative, and adaptive competencies that must be developed through competency-based, experiential, digitally supported, and context-sensitive educational approaches.

Table 1. Summary of Findings

Source	Study Title	Type of Study	Findings and Content

Alarcon-Pereira et al., 2026	Helping engineering students become better learners: An action-state orientation-based intervention study.	Empirical/Intervention study	Institutional and structural barriers—manifested as a lack of integrated educational policies, reliance on traditional pedagogical methods, resistance to innovation, insufficient infrastructure, and the absence of specialized training—along with mental and cultural obstacles, such as insufficient awareness among faculty regarding development and its necessity, rigid mindsets, and fragmented, one-dimensional curricula, impede the achievement of sustainable development in engineering education. Reforming the cognitive and attitudinal frameworks of both students and faculty plays a pivotal role in educational advancement and the realization of sustainable development. While engineering education is a fundamental pathway to this goal, an optimal model requires, first and foremost, cognitive maturity, the maturation of attitudinal domains among engineering students and faculty, and a broadened long-term perspective regarding the challenges of sustainable development
Hoang & Nguyen, 2026	An integrated STEM–CBE–ELT framework for engineering education: Bridging theory and practice in resource-constrained contexts	Conceptual/Theoretical Study	Future-oriented engineering education necessitates a transition from content-driven curricula toward competency-based and experiential learning. Even within resource-constrained environments, the quality of engineering education can be substantially enhanced through strategic instructional design.
Soufi et al. 2025	Cognitive Competencies of Students: A Systematic Review	Systematic Review	The higher education system requires further development and implementation of empowerment programs in this area. Considering the rapid and ever-increasing advancement of technology and the growing cognitive challenges associated with students' mental health and decision-making, understanding and enhancing cognitive competencies in students contribute to optimizing learning experiences and developing targeted solutions to strengthen learning strategies, cognitive transformation, and the improvement of their mental health and self-efficacy, particularly in the era of artificial intelligence governance
Armijo, 2025	Balanced profiles: The role of cognitive and non-cognitive competencies in Chilean higher education academic achievement.	Mixed-Methods Research	The role of cognitive competencies in relation to organizational change capacity and individual performance is indisputable. While leveraging cognitive competencies plays a crucial role in enhancing human capital—both for learners and in their capacities as human resources—it is important to note a significant divergence in the literature. Some studies treat individual components and attributes as distinct cognitive competencies; conversely, others advocate for the integration and synthesis of these factors, contending that it is the synergistic convergence of these elements that constitutes an individual's true cognitive competency
Gemma & Mjokaya. 2024	Influence of cognitive ability on students' academic achievement in public secondary schools in Arusha District Council	Mixed Methods Research	Cognitive competencies serve as the foundation for students' academic performance, psychological well-being, and long-term professional adaptability
AlDhaen, 2023	Education skills for digital age toward sustainable development – analysis and future direct	Synthesis of literature	There is a statistically significant difference in the cognitive skills of engineering students between their first semesters and their senior years leading up to graduation. While spatial visualization abilities show no substantial change compared to the early semesters, skills such as symbolization, numerical calculation, and numerical comprehension have demonstrated significant development. Furthermore, age is a contributing factor in the cognitive evolution of engineering students; however, gender does not exert a notable influence on cognitive development or its impact on other competencies within engineering disciplines. Consequently, supported by these cognitive abilities, the academic performance of engineering students has shown a remarkable progression
Deo et al., 2023	Critical thinking assessment in engineering education: A Scopus-based literature review	Systematic Review	Few assessments comprehensively and exclusively cover all dimensions of critical thinking, and there is a lack of consistency among the various assessment methods used in numerous studies; this constitutes a clear weakness in assessment within the field of engineering that requires further investigation and practical action.

Purwandari et al., 2022	Exploring E-Learning Community of Inquiry Framework for Engineering Education	Qualitative / Exploratory Study	Engineering education, by leveraging the salient role of cognitive factors, facilitates the development of decision-making, problem-solving, and critical thinking skills. Furthermore, strengthening pedagogical, cognitive, and social interactions promotes motivation and a collaborative spirit among engineers
Putra et al., 2021	Exploring Students' Critical Thinking Skills Using the Engineering Design Process in a Physics Classroom	Systematic Review	Engineering design and critical thinking exhibit a reciprocal relationship; specifically, the application of critical thinking significantly enhances engineering design, while engagement in engineering design fosters the development of critical thinking skills. Throughout the process of learning engineering design, students demonstrate improved reasoning, a stronger capacity for hypothesis generation and evaluation, and a more analytical perspective when solving physics problems. Consequently, it is recommended that thinking skills, particularly critical thinking, be integrated into the engineering curriculum
Mosayebi et al, 2025	Investigating and identifying the most important factors affecting the quality of teaching and learning of students of the railway engineering faculty	Descriptive-Analytical	Five key factors influencing the learning outcomes of railway engineering students were identified: satisfaction and familiarity with the field (exhibiting the highest impact); practical learning, educational facilities, and environment (exhibiting the lowest impact); as well as study habits, instructional methods, and the quality of education.
Vahdat Ghasemi et al., 2024	Explaining the necessary competencies for architecture graduates in the professional practice based on the professional competency model	Qualitative / Descriptive	In terms of professional requirements for employability among architectural engineering graduates, functional competencies hold the highest priority, whereas social competencies are ranked lowest by students
Mingaleva & Vukovic, 2020	Development of engineering students' competencies based on cognitive technologies in conditions of Industry 4.0.	Analytical-Review	Cognitive technologies foster students' conceptual understanding and problem-solving skills. The utilization of digital and smart learning environments facilitates personalized and self-regulated learning. Key competencies in the Industry 4.0 era include lifelong learning, human-machine collaboration, and proficiency in handling complex data. Consequently, to cultivate successful engineers within the Industry 4.0 landscape, educational systems must transition toward integrating cognitive technologies and smart learning methodologies
Hu & Shealy, 2022	Priming Engineers to Think About Sustainability: Cognitive and Neuro-Cognitive Evidence to Support the Adoption of Green Stormwater Design.	quantitative, experimental	Mental-cognitive arousal and preparation assist engineers in making better decisions and selecting sustainable options. Such mental-cognitive readiness enhances engineers' capacity for analytical thinking and empathy. Despite their subject matter, engineering decisions are not always purely logical or straightforward; rather, they are influenced by emotional and cognitive factors. Consequently, promoting a modern approach to engineering education requires going beyond technical training to include activities aimed at shifting engineers' mindsets and attitudes.
Zhang, 2024	Cross-cultural Engineering Team Management in The Context of globalization.	conceptual review / literature-based	Engineering education in the twenty-first century is undergoing an unprecedented transformation driven by the rapid evolution of technology, globalization, and the need for new skills to address the challenges of the modern world. Engineering education has shifted from a knowledge-based approach to a model for developing competence, reflecting a fundamental paradigm shift in the discipline. Globalization has redefined the role of engineers and requires communication skills, redefinition [of roles], and collaborative work in multidisciplinary and multicultural teams.
Tahmasebzadeh Sheikhlar et al., 2021	The role of critical thinking and entrepreneurial spirit in predicting burnout and academic procrastination of engineering students	Quantitative / Predictive	An entrepreneurial mindset alone is insufficient to mitigate academic burnout and procrastination; rather, the capacity for deep, analytical, and critical inquiry—collectively defined as critical thinking—is what enables students to effectively navigate academic challenges. As a significant cognitive construct, critical thinking plays a pivotal role in alleviating academic difficulties among engineering students. Specifically, students possessing higher levels of critical thinking skills exhibit a reduced propensity for both academic burnout and procrastination. Entrepreneurial spirit and motivation, in isolation, prove inadequate for

	addressing these issues, suggesting that other underlying cognitive or psychological variables likely play a mediating role in this relationship

Discussion and Conclusion

The findings of the present systematic review demonstrate that cognitive competencies in technical and engineering education should not be conceptualized as isolated, independent abilities; rather, they constitute an interconnected system of cognitive and self-regulatory resources that jointly support effective learning, problem solving, adaptation, and professional performance. Across the reviewed studies, critical thinking, problem solving, cognitive flexibility, self-regulation, working-memory-related processes, decision-making, and the capacity to manage complex learning demands repeatedly emerged as central dimensions of effective engineering learning. This finding supports broader conceptualizations of competency as an integrated combination of knowledge, skills, abilities, attitudes, and personal resources that become meaningful through their coordinated application in authentic situations (5-8). From this perspective, cognitive competency cannot be reduced to a single mental ability or assessed solely through performance on decontextualized tasks. Rather, it represents the capacity to mobilize several interrelated cognitive resources in response to complex educational and professional demands. This interpretation is consistent with contemporary approaches that reconceptualize knowledge, skills, and abilities as interacting components of aptitude and professional readiness (9).

One of the most important findings of the review was the central position of critical thinking within engineering cognition. The analyzed studies consistently indicated that engineering students must be capable of evaluating evidence, questioning assumptions, generating and testing hypotheses, recognizing alternatives, and making reasoned judgments in situations for which no single predetermined solution is available. This conclusion is strongly supported by previous studies demonstrating a reciprocal relationship between critical thinking and engineering design. Engagement in engineering design can promote analytical reasoning and hypothesis evaluation, while critical thinking can simultaneously improve the quality of engineering problem solving (28). The findings are also consistent with evidence indicating that critical thinking contributes to students' capacity to cope with academic challenges and is associated with lower tendencies toward academic procrastination and burnout (29). Nevertheless, the review also revealed difficulties in the systematic assessment of this competency. Previous literature has similarly identified considerable inconsistency among critical-thinking assessment approaches in engineering education, suggesting that different studies may measure different components of the construct under the same conceptual label (30). Therefore, the present results indicate that critical thinking should be treated as a multidimensional and context-dependent competency that needs to be embedded in authentic engineering learning rather than addressed as an isolated generic skill.

The findings further showed that self-regulation and the management of learning processes are fundamental components of cognitive competency. Engineering students operate within demanding educational environments in which they are expected to understand abstract concepts, integrate information across disciplines, solve open-ended problems, and sustain effort over extended periods. Under such conditions, academic success depends not only on disciplinary knowledge but also on students' capacity to plan their learning, monitor progress, select appropriate strategies, recognize ineffective approaches, and modify their behavior. Research on undergraduate engineering students has similarly demonstrated meaningful differences among students in their use of self-regulated learning strategies and in their ability to manage learning effectively (31). Furthermore, interventions targeting action-state orientation indicate that engineering students can be supported in becoming more effective learners when educational activities explicitly address how intentions are translated into sustained and organized academic behavior (32). These findings reinforce the conclusion that self-regulation should not be viewed merely as a supplementary study habit; it represents a core mechanism through which other cognitive competencies are coordinated and transformed into effective performance.

Another central finding concerned the close association between cognitive competencies and deep, durable, and transferable learning. The reviewed evidence suggested that students may possess substantial theoretical knowledge while remaining unable to apply that knowledge effectively in unfamiliar or ambiguous situations when relevant cognitive capacities have not been sufficiently developed. This result is compatible with the broader literature emphasizing that cognitive competencies play a foundational role in academic performance, adaptation, decision-making, and long-term learning (25, 26). It also supports arguments that optimal educational performance depends on balanced profiles that combine cognitive and non-cognitive competencies rather than privileging one domain exclusively (27). In engineering education, this issue is particularly important because professional problems frequently require students to transfer principles learned in formal instructional settings to situations that differ substantially from textbook examples. Consequently, cognitive competency-based education should prioritize students' capacity to reorganize and use knowledge rather than the mere accumulation of information.

The results also indicated that cognitive competency is inherently contextual and dynamic. Cognitive resources are not expressed identically across all situations; their manifestation depends on interactions among the learner, the nature of the task, the educational environment, and professional expectations. This finding is consistent with contextualized perspectives of employability, which argue that individual resources produce different outcomes depending on the opportunities, constraints, and demands present within specific environments (10). Evidence from different areas of engineering education further supports this conclusion. In railway engineering, learning quality has been associated with students' satisfaction and familiarity with the discipline, practical learning opportunities, instructional methods, study habits, facilities, and the educational environment (42). Similarly, investigations of competencies required for architectural practice show that the relative importance of specific competencies is shaped by professional demands rather than by academic assumptions alone (41). These findings suggest that cognitive competencies cannot be meaningfully developed or assessed without considering the settings in which they are expected to operate.

A further important result concerned the value of active, experiential, and competency-based educational approaches. The reviewed studies suggested that cognitive competencies develop most effectively when students engage with authentic or simulated professional problems requiring active decision-making, collaboration, design, reflection, and application of disciplinary knowledge. Robotics-centered project-based learning provides one example of how students can integrate conceptual knowledge with design, construction, experimentation, and problem solving within meaningful engineering tasks (1). Similarly, the integration of STEM, competency-based education, and experiential learning has been proposed as a pathway for reducing the gap between theoretical instruction and professional application, including in resource-constrained settings (2). Challenge-based educational models such as Tec21 further demonstrate how learner-centered and interdisciplinary experiences can organize education around complex challenges rather than discrete disciplinary content (38). Together, these studies support the present finding that cognitive competencies are best developed through curricular experiences that require their repeated use rather than through isolated instruction about the competencies themselves.

The findings regarding digital transformation and Industry 4.0 further extend this argument. Engineering students increasingly require competencies for working with complex data, intelligent systems, automated environments, and continuously evolving digital technologies. Previous research has emphasized that cognitive technologies and smart learning environments may support conceptual understanding, personalized learning, problem solving, and self-regulated learning while simultaneously creating demand for new forms of human-machine collaboration (33). The increasing use of generative artificial intelligence in engineering education likewise requires students to develop competencies not only for operating such systems but also for evaluating generated information, making responsible decisions, and integrating AI outputs with disciplinary reasoning (34). Moreover, AI-supported tools for competency-based assessment demonstrate that digital technologies may help educators map and evaluate competencies more systematically (35). However, the present findings suggest that these technological applications will be educationally meaningful only when the competencies being developed or assessed are conceptually well defined and connected to authentic engineering performance.

The review also revealed that cognitive competencies are closely connected with the interpersonal and collaborative requirements of contemporary engineering. Modern engineering practice is rarely an exclusively individual activity; rather, engineers frequently participate in multidisciplinary, geographically dispersed, and culturally diverse teams. Consequently, effective performance requires the interaction of cognitive processes with teamwork, communication, leadership, and conflict-management abilities. Previous research demonstrates that engineering students recognize the importance of team culture, role distribution, responsibility, peer interaction, and constructive responses to underperforming team members (21). Faculty members have similarly identified deficiencies and developmental needs in engineering students' leadership preparedness (22). Globalization further intensifies these demands because engineers increasingly need to collaborate across linguistic, disciplinary, and cultural boundaries (20). Teaching approaches combining flipped learning, cooperative work, and gamification have also demonstrated potential for developing soft skills in engineering students (23). Accordingly, the present findings imply that cognitive competency development should not be artificially separated from interpersonal learning, because real engineering problems require simultaneous cognitive and social coordination.

Professional identity represents another important dimension for interpreting the results. Competency development occurs not only through acquiring abilities but also through gradually learning what competent professional action means within a particular field. Research on professional identity formation emphasizes the roles of competence, belonging, mattering, recognition, and participation in helping students develop a stable professional self-concept (15, 16). Other scholarship has argued that competency-based education and professional identity formation should be integrated rather than treated as competing educational paradigms (17). Similar patterns of identity development have been reported in professional education more broadly, where exposure to practice settings and professional communities contributes to students' evolving understanding of their roles (18). Civic identity scholarship additionally highlights the importance of values and participation in educational development (19). From this perspective, cognitive competency-based engineering education should help students not only perform tasks successfully but also understand how competent reasoning, judgment, responsibility, and learning are embedded within professional engineering identity.

The results also support the growing importance of employability as an outcome of competency development, while simultaneously indicating that employability should not be understood narrowly. Traditional studies have emphasized the importance of communication, teamwork, professionalism, self-direction, uncertainty management, and transferable skills for graduates' transition to employment (11, 12). More recent evidence confirms that twenty-first-century employability depends upon combinations of technical, cognitive, interpersonal, digital, and adaptive capacities (14). At the same time, the ongoing debate regarding employability as a core responsibility of higher education illustrates that universities cannot simply equate educational quality with short-term labor-market placement (13). Graduate competence should therefore include the capacity for continued learning and adaptation across changing occupational circumstances. Apprenticeship-oriented studies reinforce this developmental perspective by showing how professional growth can occur through sustained participation in authentic occupational environments (24). Similarly, the use of successful graduates as sources of evidence for curriculum improvement demonstrates the value of connecting educational design to actual professional trajectories (44).

The systematic review additionally showed that sustainability-related engineering decisions illustrate the complexity of cognition in professional practice. Engineering decision-making cannot always be represented as a purely technical or mathematically optimized process because environmental decisions may also involve values, perception, framing, and emotional-cognitive responses. Neurocognitive evidence suggests that appropriate priming can influence engineers' thinking and increase their consideration of sustainable design alternatives (39). Broader analyses of engineering education for sustainable development similarly identify institutional and pedagogical obstacles, including fragmented curricula, reliance on traditional methods, inadequate infrastructure, resistance to innovation, and limited awareness among educators (3). Competencies required for sustainable development in the digital age consequently include analytical ability, adaptation, continuous learning, and capacity to address multidimensional problems (40). These findings further substantiate the central conclusion of the present review that engineering cognition is multidimensional and cannot be adequately developed through technical instruction alone.

Finally, the findings indicate that engineering education is undergoing a broader transition from knowledge transmission toward competency development. Internationalization, technological transformation, artificial intelligence, sustainability, and changing labor-market expectations have collectively expanded the responsibilities of engineering programs. International mobility among STEM students reflects the emergence of a global educational and professional knowledge space in which students seek learning opportunities according to perceived academic and occupational possibilities (43). At the macro level, educational investment, inclusion, and lifelong learning are increasingly regarded as elements of economic and social development (4). Educational institutions must therefore create curricula that allow students to continually develop and renew cognitive competencies throughout their professional lives. The central implication of the present review is that cognitive competency-based technical and engineering education requires a holistic curricular architecture in which critical thinking, problem solving, self-regulation, cognitive flexibility, decision-making, teamwork, and adaptive learning are developed through coherent, progressively challenging, and context-sensitive educational experiences rather than taught as disconnected supplementary skills.

The present systematic review has several limitations that should be considered when interpreting its findings. First, although the search strategy covered several major international and Iranian scientific databases, relevant studies indexed in other specialized, regional, or non-indexed sources may not have been identified. Second, the included studies were heterogeneous in research design, engineering discipline, educational setting, participant characteristics, conceptual definitions, and methods used to evaluate cognitive competencies, which limited the possibility of direct comparison across studies. Third, considerable conceptual overlap was observed among constructs such as cognitive competency, metacognition, self-regulation, critical thinking, employability skills, and professional competencies, making strict classification difficult. Fourth, the limited number of studies meeting the final inclusion criteria restricts the generalizability of the synthesized framework across all technical and engineering disciplines. Finally, because the review synthesized published evidence, its conclusions remain dependent on the methodological quality, conceptual clarity, and reporting practices of the original studies and may also be affected by publication bias.

Future studies should empirically examine the relationships among the cognitive competencies identified in this review rather than investigating them separately. Longitudinal designs are particularly needed to determine how critical thinking, problem solving, cognitive flexibility, self-regulation, working memory, and decision-making develop across different stages of engineering education and how changes in these competencies predict academic and professional outcomes. Researchers should also distinguish more precisely among cognitive, metacognitive, motivational, emotional, and interpersonal competencies and develop validated multidimensional instruments that capture their interrelationships. Comparative research across engineering disciplines, universities, cultural settings, and national higher-education systems would clarify the extent to which cognitive competency models are context-specific or generalizable. Future studies could additionally examine the effects of project-based learning, problem-based learning, artificial intelligence, virtual laboratories, simulation, apprenticeships, and industry-based learning on competency development through experimental or quasi-experimental designs. Particular attention should also be directed toward university-industry relationships and the role of institutional policies, curricular structures, faculty competencies, and organizational resources in facilitating or constraining the development of students' cognitive competencies.

Engineering universities and faculties should explicitly incorporate cognitive competencies into curriculum objectives, course design, teaching strategies, and assessment systems instead of assuming that these abilities will develop automatically through exposure to technical content. Programs should provide progressively complex learning experiences in which students repeatedly practice critical thinking, problem solving, decision-making, self-regulation, teamwork, and adaptation in authentic or simulated engineering situations. Project-based learning, interdisciplinary design problems, case studies, laboratory challenges, industry partnerships, internships, reflective activities, and collaborative assignments can be used to connect theoretical knowledge with professional action. Faculty-development programs should also prepare instructors to teach and assess cognitive competencies using clear performance criteria and authentic assessment tasks. Universities should establish mechanisms for regular feedback from employers, graduates, professional associations, and students so that competency frameworks remain responsive to technological and occupational change. Finally, cognitive competency development should be approached as a continuous process extending across the entire engineering curriculum, with introductory courses establishing foundational abilities and advanced courses requiring increasingly independent, integrated, and context-sensitive application.

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Authors’ Contributions

All authors equally contributed to this study.

Declaration of Interest

The authors of this article declared no conflict of interest.

Ethical Considerations

All ethical principles were adhered in conducting and writing this article.

Transparency of Data

In accordance with the principles of transparency and open research, we declare that all data and materials used in this study are available upon request.

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