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A Systematic Literature Review on Research Trends and Pedagogical Patterns in Teaching Fluid Mechanics 2024

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Abstract

Despite growing interest in innovating fluid mechanics education, teaching strategies and learning outcomes often remain fragmented rather than systematically aligned. This study aims to comprehensively examine global research trends and pedagogical patterns in fluid mechanics education within higher science education. An integrated approach combining bibliometric analysis and qualitative meta-analysis through a systematic literature review (SLR) was employed. A total of 326 Scopus-indexed publications published between 2019–2025 were analyzed using the Bibliometrix package in RStudio for performance analysis, while 35 selected studies were further examined through PRISMA-guided qualitative coding using NVivo software. The findings reveal a rapidly growing research field, although international collaboration remains limited. Thematic analysis indicates a strong shift toward student-centered and technology-enhanced pedagogies, particularly flipped classrooms, simulation-based learning, and computational instruction. However, instructional strategies are predominantly implemented in isolation, with limited integration across learning designs. Consequently, learning outcomes—such as conceptual understanding, problem-solving skills, and computational competencies—remain insufficiently aligned. Overall, this study highlights a critical gap in unifying pedagogical approaches, instructional strategies, and learning outcomes within coherent frameworks. Future research should develop and empirically validate integrated, technology-supported instructional models to foster holistic, transferable learning in higher education fluid mechanics.

How to Cite

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INTRODUCTION

Fluid mechanics is a fundamental branch of physics essential for scientific understanding and practical applications across natural systems, environmental processes, and modern engineering (Chashechkin, 2021; Gray et al., 2021; Kundu et al., 2024; Supriyono, 2019; Vaidya, 2020). Taught across diverse science and engineering disciplines, including physics, mathematics, and mechanical, chemical, and civil engineering. It spans from school curricula to higher education (Castilla & Peña, 2023; Cengel, 2024; Vaidya, 2020). Despite its foundational status, discussions regarding interdisciplinary teaching strategies remain limited (Vaidya, 2020). Without effective instructional approaches, students and prospective teachers struggle to connect abstract theories with practical applications, while traditional lectures inadequately foster active, collaborative learning (Børte et al., 2023; Liuta et al., 2019; Mollick & Mollick, 2023). Furthermore, research on fluid mechanics education remains fragmented across contexts, hindering the development of a coherent scholarly body (Solmaz et al., 2024). Identifying evidence-based instructional strategies is therefore vital for improving learning outcomes (Huilier, 2019).

Curricular content in higher education typically progresses from introductory fluid statics (hydrostatics, buoyancy, stability) to kinematics and dynamics governed by mass, momentum, and energy conservation laws, notably Bernoulli's equation (Díaz et al., 2023; Ulazia & Ibarra-Berastegi, 2020; Vanoye-Garcia, 2024). Core topics expand to viscosity, pipe flow, nondimensional parameters like the Reynolds number, dimensional analysis, and turbomachinery (Bhagavanulu, 2020; Ulazia & Ibarra-Berastegi, 2020; Vanoye-Garcia, 2024). Modern engineering curricula increasingly integrate computational fluid dynamics (CFD), molecular dynamics, and experimental visualization methods such as particle image velocimetry (PIV), often within problem-based learning (PBL) and sustainability frameworks (Boettcher, 2023a; Muriithi et al., 2025; Pinto, 2022; Shi, 2022; Ulazia & Ibarra-Berastegi, 2020; Vanoye-Garcia, 2024). However, distinct disciplinary emphases exist: engineering education prioritizes mathematical formalism and analytical design, whereas science education focuses on conceptual understanding, qualitative reasoning, and scientific literacy (Díaz et al., 2023; Vanoye-Garcia, 2024).

This disciplinary divergence shapes student difficulties. Across educational contexts, fluid mechanics is perceived as challenging due to abstract representations, conceptual complexity, and heavy mathematical demands (Díaz et al., 2023; Vanoye-Garcia, 2024). In science education, challenges are predominantly conceptual; counterintuitive phenomena like pressure variation, buoyancy, and flow continuity conflict with everyday intuition, producing persistent misconceptions (Ayala et al., 2022; Díaz et al., 2023; Frances Yraguen, 2022). Principles such as Bernoulli's equation are frequently treated as static formulas rather than conditional relationships derived under specific physical constraints (Vanoye-Garcia, 2024). In engineering education, difficulties stem from linking vector calculus and differential equations to physical flow phenomena, leading to procedural problem-solving that fails to transfer to open-ended challenges (Díaz et al., 2023; Pinto, 2022). In both settings, traditional lecture-centered delivery and reliance on idealized models exacerbate cognitive load and obscure real-world relevance (Díaz et al., 2023; Muriithi et al., 2025; Vanoye-Garcia, 2024). Mitigating these obstacles requires instructional models sensitive to both conceptual and analytical demands, explicitly bridging physical intuition with mathematical reasoning.

Literature reviews are essential for synthesizing existing scholarship, identifying dominant themes, and revealing research gaps (Snyder, 2019). Existing bibliometric studies in fluid mechanics have largely focused on subfields such as artificial intelligence (Zhang et al., 2025), chemical engineering (Nandiyanto et al., 2025), computational approaches like lattice Boltzmann methods and vortex-induced vibration (Alias & Rahman, 2024; Li et al., 2020; Zhang et al., 2024), and environmental applications like wind tunnels and marine design (Lande et al., 2023; Mo & Liu, 2023; Zeng et al., 2021). While these studies effectively map technological advancements and research trends, they omit pedagogical perspectives (Ozturk, 2021). Recent educational bibliometric work remains heavily confined to engineering contexts, neglecting broader science education and teacher preparation programs (Altun & Yildirim, 2023).

To address these gaps, this study adopts an integrated framework combining bibliometric analysis and a systematic literature review (SLR) to comprehensively map publication trends and synthesize pedagogical strategies, instructional designs, and learning outcomes in higher science and engineering education. To guide this investigation, the study addresses the following Research Questions (RQs):

RQ1 : What are the global trends in publication and citation growth related to teaching fluid mechanics in higher education during 2019–2025?

RQ2 : What are the dominant research themes, topics, and keywords in research on teaching fluid mechanics?

RQ3 : What pedagogical approaches, instructional strategies, and targeted learning outcomes are most frequently identified in systematic literature on fluid mechanics education?

METHOD

Method used should be accompanied by references, relevant modification should be explained. Procedure and data analysis technique should be emphasized to literature review article. This study integrates bibliometric analysis and SLR to examine global research trends in the teaching of fluid mechanics in higher science education. In addition, it synthesizes pedagogical approaches, instructional strategies, and emerging themes to provide an evidence-based foundation for curriculum development, instructional design, and future research. The bibliometric approach was selected because it offers a systematic, objective, and reproducible method for mapping research trends, identifying influential contributors, and tracing thematic development within fragmented research landscapes (Donthu et al., 2021). At its core, bibliometric analysis provides two complementary perspectives: performance analysis and science mapping (Donthu et al., 2021; Lim et al., 2024; Mukherjee et al., 2022).

To answer RQ1 and RQ2, science mapping was employed to examine publication trends, thematic evolution, and the conceptual structure of research on fluid mechanics education (Gutiérrez-Salcedo et al., 2017). The analysis further incorporated citation analysis and keyword co-occurrence analysis to capture intellectual linkages and emerging research themes (Luo et al., 2022). To ensure methodological rigor and transparency, the study followed established bibliometric research guidelines (Donthu et al., 2021) and adhered to the PRISMA 2020 statement for the SLR process (Page et al., 2021). Together, these methods provide both a macro-level overview of research dynamics and a micro-level understanding of educational practices in fluid mechanics within higher science education.

Database Selection and Search Strategy

To address the research questions, a comprehensive literature search was conducted in Scopus, which served as the sole data source for both the bibliometric analysis and the qualitative meta-analytic synthesis to ensure data quality and methodological consistency. Scopus was selected for its extensive multidisciplinary coverage, neutrality, and suitability for bibliometric and meta-analytic research, particularly in engineering, science, and education (Baas et al., 2020; Gray et al., 2021; Kahraman, n.d.; Khan et al., 2022; Thu et al., 2021; Vargas-Quesada et al., 2023). A structured keyword search was applied to retrieve relevant publications, with records exported in BibTeX format for bibliometric analysis (Lim et al., 2024) and CSV format for the SLR to ensure compatibility with the analytical tools and efficient screening.

Table 1 summarizes the database selection criteria and search parameters adapted from Alias and Rahman (2024). A comprehensive search strategy was constructed using combinations of keywords and Boolean operators, including AND and OR, as detailed in Table 1, to ensure broad and relevant literature coverage. The inclusion criteria for the SLR, presented in Table 1, were applied to ensure consistency in scope, quality, and educational focus, following established review methodologies (Hennessy et al., 2019).

Table 1. Summary of database and selection criterion (Alias & Rahman, 2024)

Category	Specific Standard Requirements
Database	Scopus
Search strings	"Teaching" OR "Learning" OR "Instruction" OR "Education" AND "Fluid Mechanics" OR "Fluids"AND "Higher Education" OR "University" OR "College" OR "Undergraduate"
Searching Periode	2016-2025
Document type	Article, conference paper
Language	English
Data Export Format	CSV and Bibtex

As additional inclusion criteria during the SLR data analysis phase, the following aspects were applied: (1) topic relevance, referring to studies directly related to the teaching and learning of fluid mechanics or fluid dynamics; (2) educational level, focusing on higher education contexts at the undergraduate or graduate level; (3) study originality, including only original and non-duplicated research articles; and (4) accessibility, restricting the review to open-access journal articles and conference proceedings to ensure full-text availability. The complete study selection process is illustrated in the PRISMA flow diagram (see Figure 1), ensuring transparency, reproducibility, and methodological rigor.

Software Selection

In this study, bibliometric analysis addressed RQ1 and RQ2 using data from 326 Scopus-indexed records analyzed with the Bibliometrix package and Biblioshiny interface in RStudio (Aria & Cuccurullo, 2017). In addition, to address RQ3, the systematic review was conducted using the Watase UAKE platform (watase.web.id), a web-based tool developed to support SLR in alignment with the PRISMA 2020 guidelines. The systematic review was structured into four stages: identification, screening, eligibility, and inclusion (Khan et al., 2022; Page et al., 2021; Vargas-Quesada et al., 2023). The platform is directly integrated with the Scopus database, allowing efficient identification and retrieval of relevant publications. All records obtained from the search were organized and processed within the platform to support duplicate detection, title and abstract screening, and final article selection for analysis. The integration of bibliometric techniques and the PRISMA-guided review strengthened both the quantitative mapping and qualitative synthesis of the research field.

To further support the inclusion stage, qualitative data analysis was conducted using NVivo. This software facilitated the systematic coding and categorization of selected articles, enabling a more rigorous and transparent inclusion process. Through NVivo, relevant themes, patterns, and relationships within the final set of studies were identified and analyzed, thereby enhancing the depth and reliability of the qualitative synthesis.

Data Analysis

The selected articles were analyzed using a two-stage analytical approach that integrated bibliometric techniques and qualitative content analysis. First, the finalized dataset (n = 326) was exported in a compatible format and processed using the Bibliometrix package in R and its Biblioshiny interface. This stage involved performance analysis, including publication trends and the most productive authors, sources, and countries, as well as science mapping techniques, including keyword co-occurrence analysis, thematic mapping based on centrality–density analysis, and thematic evolution to identify dominant, emerging, and declining research themes.

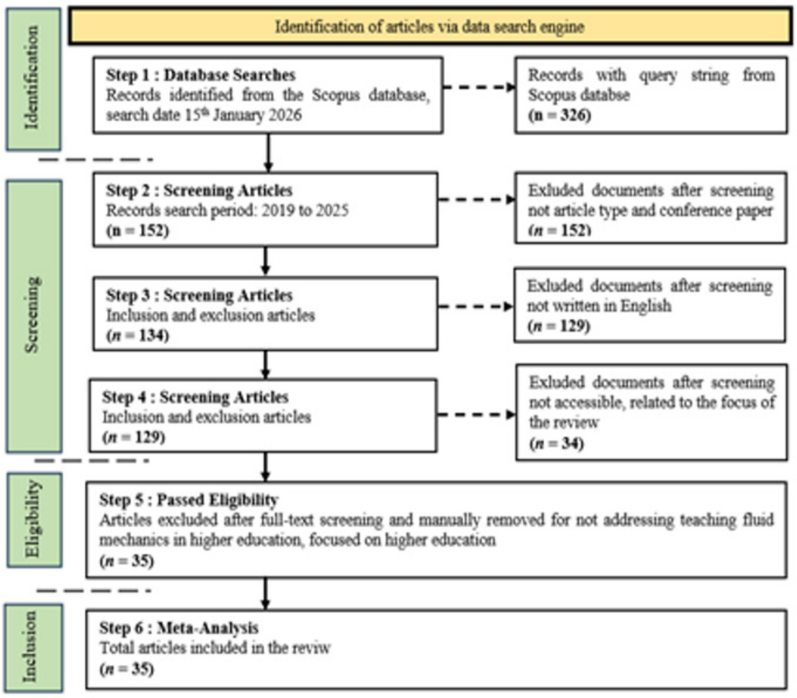

Figure 1. Processing of document eligibility based on PRISMA guideline

Second, a qualitative synthesis was conducted to complement the bibliometric findings. Articles were systematically coded based on key dimensions, including research focus, instructional strategies, learning approaches, and educational contexts. An inductive-deductive coding approach was applied, allowing patterns to emerge from the data while remaining guided by the research questions. The results of this stage were used to interpret pedagogical trends and conceptual developments within fluid mechanics education. The integration of these two analytical approaches enabled a comprehensive understanding of both the structural patterns of the literature and the underlying pedagogical insights, thereby ensuring a robust and multidimensional interpretation of the research field.

RESULT AND DISCUSSION

RQ1. Trends in Publications and Citations on Teaching Fluid Mechanics (2019–2025)

To address RQ1, a bibliometric performance analysis was conducted to examine global trends in publication growth and citation impact in research on teaching fluid mechanics in higher science education during 2019–2025. The overall bibliometric dataset encompasses 187 documents published across 135 scholarly sources, reflecting an annual growth rate of 28.75%. This rapid expansion underscores growing academic attention to fluid mechanics pedagogy. The scholarly landscape comprises 626 distinct authors with a strong emphasis on collaborative authorship, evidenced by an average of 3.44 co-authors per publication and only 36 single-authored documents. However, international co-authorship remains modest at 17.11%, indicating that research activities are still largely concentrated within national or regional networks. The corpus demonstrates substantial thematic diversity with 761 author keywords, while an average document age of 3.42 years and 9.67 citations per document indicate an active, highly recent, and moderately cited body of literature.

Figure 2. Bibliometric performance indicators of research on teaching fluid mechanics in higher science education (2019–2025)

Source distribution follows Bradford's Law, exhibiting a core zone of primary outlets alongside a long tail of scattered publications. Key core journals driving this domain include BMC Medical Education, Education Sciences, and Computer Applications in Engineering Education. Beyond this primary tier, publication output disperses broadly across interdisciplinary venues spanning science education, engineering instruction, and applied pedagogical research.

RQ2. Dominant Research Themes, Topics, and Keywords

Keyword co-occurrence and thematic mapping using centrality-density analysis revealed the conceptual structure of the field across four primary quadrants:

1. Motor Themes (High Centrality, High Density): Highly relevant and theoretically well-developed themes that drive the field, including students, engineering education, fluid mechanics, curricula, and cognition. The presence of ecological systems theory reflects an increasing shift toward examining learning through sociocultural and systemic lenses.
2. Basic Themes (High Centrality, Low Density): Foundational topics that are widely connected across the literature but remain less theoretically consolidated, such as student experiences, international students, identity, hands-on learning, and multilingualism.
3. Niche Themes (Low Centrality, High Density): Specialized and internally developed strands with limited influence on the broader field, including teaching and learning, laboratory instruction, systematic review, and upper-division undergraduate education.
4. Emerging or Declining Themes (Low Centrality, Low Density): Exploratory or highly topic-specific domains, such as machine learning, translanguaging, Archimedes' principle, and static fluid.

Keyword frequency analysis corroborates these thematic patterns. The primary focus centers on student populations in higher education settings (students, higher education, curricula, engineering education). Secondary tiers emphasize interdisciplinary instruction (fluid mechanics, medical education) and demographic factors (female, male). Key pedagogical terms-such as problem-based learning, active learning, computer-aided instruction, e-learning, and pandemic-driven terms like COVID-19-highlight a broad transition toward technology-supported and student-centered learning environments.

RQ3. Pedagogical Approaches, Instructional Strategies, and Targeted Learning Outcomes.

Qualitative synthesis through a systematic literature review (SLR) categorized the pedagogical features across macro, meso, and micro levels:

1. Macro-Level Pedagogical Approaches: Research predominantly adopts student-centered learning (e.g., flipped classrooms, inquiry-based learning, problem-based learning) and technology-enhanced learning (e.g., simulation-based learning, computational instruction using tools like MATLAB, and emerging learning analytics). Experiential and applied learning approaches are also moderately represented.
2. Meso-Level Instructional Strategies: Specific practices used to operationalize macro-level approaches include numerical modeling, interactive CFD simulations and dynamic visualizations, blended instructional designs, guided problem-solving with worked examples, collaborative group tasks, learning analytics monitoring, and metacognitive scaffolding.
3. Micro-Level Targeted Learning Outcomes: Instructional designs target outcomes across three main domains: cognitive/conceptual (conceptual understanding, mathematical reasoning, conceptual–mathematical integration), higher-order thinking (problem-solving, critical thinking, metacognition), and computational/digital skills (computational thinking, numerical analysis, data interpretation).

Combining bibliometric performance analysis and qualitative synthesis highlights both the rapid expansion and the conceptual fragmentation of fluid mechanics education research. The strong annual growth rate aligns with broader STEM initiatives aimed at adopting evidence-based active learning models. However, the modest rate of international co-authorship confirms that research remains localized, limiting the establishment of globally cohesive pedagogical frameworks.

A critical gap identified across all three analytical levels is structural misalignment. At the macro level, student-centered and technology-enhanced frameworks are widely praised but frequently deployed independently rather than within unified learning designs. At the meso level, strategies like CFD simulations or numerical modeling are regularly applied as isolated visualization tools rather than being embedded into inquiry-based or problem-based sequences. At the micro level, learning outcomes are often bifurcated—focusing either on conceptual intuition or on mathematical/computational execution. This separation exacerbates student difficulties in bridging mathematical formulations with physical fluid phenomena. Addressing these challenges requires future research to develop and empirically validate integrated, multi-modal instructional frameworks that explicitly combine project-based learning, simulation technology, and metacognitive scaffolding.

CONCLUSION

This study provides a comprehensive synthesis of global research trends, dominant thematic structures, and pedagogical patterns in fluid mechanics education within higher science education through an integrated bibliometric analysis and systematic literature review. The synthesized findings demonstrate that while scholarly interest and publication output in fluid mechanics pedagogy have expanded rapidly across diverse international sources, research collaborations remain largely localized within regional boundaries, highlighting a need for stronger global integration. Thematically, the domain is grounded in cognitive processes, curriculum design, and student learning transitions, though foundational sociocultural dimensions, such as student identity, experiential learning, and multilingualism remain insufficiently integrated into existing theoretical models. Crucially, while higher education instruction has shifted away from traditional lecture formats toward student-centered and technology-enhanced approaches, a pervasive structural misalignment persists across pedagogical frameworks, instructional strategies, and targeted learning outcomes. Innovative tools such as interactive computational simulations, numerical modeling, and problem-based tasks are frequently deployed as isolated instructional interventions rather than as part of cohesive, intentionally sequenced learning designs, which ultimately hinders students' ability to synthesize conceptual reasoning with mathematical and computational skills. This study is primarily limited by its reliance on published literature within specific index boundaries, which may overlook contextual nuances in localized classroom implementations. To address these gaps, future research should focus on designing and empirically validating integrated, technology-supported instructional frameworks that explicitly align active learning strategies with metacognitive scaffolding to foster holistic conceptual understanding, critical thinking, and transferable problem-solving capabilities in higher science education.

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