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Scientific and methodological foundations for teaching physicochemical analysis methods in continuous chemical education: a scoping review

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Background: Rapid technological advancement, digitalization of analytical instrumentation, and the growing demand for interdisciplinary competence have significantly transformed the role of analytical chemistry in science and industry. These changes necessitate a systematic reconsideration of how physicochemical analysis methods are taught within continuous chemical education.

Objective: This scoping review aimed to map and systematize the structural components of modern analytical chemistry education, identify dominant pedagogical approaches, and conceptualize their functional interrelationships within an integrated educational framework.

Design/methods: The study was conducted as a scoping review in accordance with PRISMA-ScR guidelines. A comprehensive search was performed in Scopus, Web of Science, ScienceDirect, ACS Publications, SpringerLink, and RSCI (eLIBRARY.ru), covering publications from 1975 (the earliest eligible record retrieved) to 2024. Eligible studies addressed pedagogical, curricular, or methodological aspects of teaching analytical chemistry or physicochemical analysis methods. Extracted data were analyzed using qualitative thematic synthesis and conceptual mapping to identify recurring educational components and trends.

Results: The analysis revealed a consistent shift from method-centered instruction toward competence-oriented and system-based educational models. The most frequently reported components included integration of theoretical principles with laboratory practice, problem-based and research-oriented learning, incorporation of digital tools and chemometrics, emphasis on metrology and data interpretation, and increasing attention to sustainability and green analytical chemistry. The evidence indicates a transition from isolated presentation of analytical techniques to structured training focused on analytical thinking, decision-making, and interpretation of complex data.

Conclusions: Modern analytical chemistry education is evolving toward an integrated, interdisciplinary, and competence-driven model that prioritizes conceptual understanding, information processing, and real-world problem solving. The structural framework identified in this review may support curriculum development, modernization of laboratory courses, and alignment of educational programs with contemporary scientific and industrial demands.

KEYWORDS

analytical methods, chemistry teaching methods, competence-based approach, continuous chemical education, educational technologies, physical and chemical analysis

1 Introduction

Modern advances in chemical science, analytical technologies, and instrumental methods place new demands on the training of specialists in analytical chemistry. Analytical chemistry today represents not only a set of methods for determining the composition and properties of substances, but also an interdisciplinary field providing reliable information necessary for solving scientific, industrial, environmental, medical, and technological problems. Under these circumstances, improving analytical chemistry teaching methods and building a comprehensive training system focused on developing students' deep theoretical knowledge, strong practical skills, and analytical thinking are particularly pressing (Correia et al., 2025; Wenzel et al., 2022).

Traditional approaches to teaching analytical chemistry, focused primarily on imparting theoretical material and reproducing standard laboratory techniques, are reported by several authors to be losing effectiveness (Correia et al., 2025; Wenzel et al., 2022). The modern educational paradigm requires a shift in emphasis toward results-oriented learning, developing skills in solving complex analytical problems, working with real-world analytical objects, interpreting experimental data, and understanding the role of analytical measurements in socially significant contexts. In this regard, active and cooperative learning, project-based laboratory work, and the use of modern instrumental analytical methods are particularly important (Wenzel et al., 2022).

This paper examines approaches to organizing the educational process in analytical chemistry, focusing on student-centred learning, integrating theoretical and practical training, and developing students' professional and cross-professional competencies. Attention is paid to the role of cooperative learning and complex laboratory projects as effective means of developing a holistic understanding of analytical chemistry and increasing students' motivation to study the discipline.

For the purposes of this review, continuous chemical education is operationally defined as the articulated progression of analytical-chemistry instruction across secondary/pre-university preparation, undergraduate and postgraduate university training, and the continuing professional development of practising analysts, whereby competencies developed at one stage are deliberately built upon at subsequent stages. This definition is applied throughout the review to classify and compare the included studies by educational level. Of the 48

sources in the reference list for which an educational level could be identified from the source itself (Table 1), essentially all explicitly identified cases concern the university/undergraduate level, and none explicitly concern secondary/pre-university education or continuing professional development as a distinct focus; the remaining sources do not state an educational level. On this basis, the continuity claim in the title and Conclusion is presented deliberately as a conceptual/operational continuum rather than as an empirical finding that all stages are evenly represented in the evidence base; readers should not infer balanced coverage across educational levels from the title. The full set of 48 included studies (Section 2, Table 2) has been captured in Table 1, so this assessment reflects the complete reference list rather than a partial sample.

Terminological note: this review uses “results-oriented learning,” “competence-oriented education,” and “competency-based education” interchangeably to denote instruction organized around demonstrable learning outcomes and competencies rather than content coverage alone; this usage is applied consistently throughout the text.

Although the reorientation of analytical-chemistry curricula toward competence-based, student-centred, and technology-enhanced instruction has been discussed in prior disciplinary commentaries and narrower topical reviews – for example, a systematic review and meta-analysis of pedagogical approaches in secondary-level chemistry education more broadly (Ahmad et al., 2023), which is general in scope and does not address analytical chemistry specifically or continuity across educational levels – a systematic mapping that integrates pedagogical approaches, digital tools, sustainability-oriented content, and metrological competence into a single conceptual framework across the full span of continuous chemical education has not, to our knowledge, been previously undertaken. The present scoping review addresses this gap by (i) systematically identifying the structural components reported in the literature on analytical chemistry education, (ii) mapping their conceptual interrelationships, and (iii) proposing an integrated framework intended to support curriculum development. The review is structured around the explicit review questions formulated in Section 2.3. Throughout this review, physicochemical analysis methods are treated as the representative methodological core of analytical chemistry education: eligible studies address the teaching of physicochemical (physical and chemical) analysis techniques specifically, and are discussed within the broader disciplinary and pedagogical context of analytical chemistry

TABLE 1 Characteristics of the 48 sources cited in this review's reference list, compiled from the bibliography and from the descriptions already given for each source in [sections 3–10](#) above.

No.	Author/Year	Country	Educational level	Publication type/design	Population	Pedagogical strategy	Analytical method
1	Kissinger, 1992	USA	n/s	Journal article (editorial/commentary)	n/s	n/s	n/s
2	Pungor, 1981	Western Europe	n/s	Journal article	n/s	n/s	n/s
3	Zolotov, 2000	Russia	University	Journal article (departmental account)	n/s	n/s	n/s
4	Malissa, 1981	Western Europe (Austria)	n/s	Journal article	n/s	n/s	n/s
5	Pungor and Kellner, 1988	Western Europe	n/s	Journal article	n/s	n/s	n/s
6	Valcárcel and Ríos, 1997	Western Europe	n/s	Journal article	n/s	Systematic introduction of analytical-properties concepts	n/s
7	Zolotov, 2011	Russia	n/s	Journal article	n/s	n/s	n/s
8	Malissa, 1987	Western Europe (Austria)	n/s	Journal article	n/s	n/s	n/s
9	Grasselli, 1977	USA	n/s	Journal article	n/s	Focus on real-world analytical tasks	n/s
10	Burns, 2002	Western Europe	n/s	Journal article (historical review)	n/s	n/s	n/s
11	Otto, 2001	Western Europe	n/s	Journal article	n/s	Interdisciplinary curriculum integration	n/s
12	Stone, 2005	Western Europe (UK)	n/s	Journal article (commentary)	n/s	n/s	n/s
13	Valcárcel, 2001	Western Europe	n/s	Journal article	n/s	n/s	n/s
14	Vershinin, 2003	Russia	University	Journal article	n/s	n/s	n/s
15	Sommer, 1993	Western Europe	Undergraduate	Journal article	Undergraduate students	n/s	n/s
16	Calascibetta et al., 2000	Western Europe (Italy)	n/s	Journal article	n/s	Interdisciplinary teaching via an aquarium project	n/s
17	Jacobsen, 1979	Western Europe (Norway)	n/s	Journal article	Medical laboratory technologists (per review text)	Integration with clinical chemistry and long-term lab practice	n/s
18	Postigo et al., 2021	Eastern Europe (Brazil)	n/s	Journal article	n/s	Constructivist laboratory workshop	Qualitative chemical analysis (cation reactions)
19	Kurowska-Susdorf et al., 2019	Western Europe	n/s	Journal article	n/s	Integration of green/sustainability principles	Green analytical chemistry
20	Chalmers, 1978	Western Europe	n/s	Journal article	n/s	Reflective/discussion-based pedagogy	n/s

(Continued)

TABLE 1 Continued

No.	Author/Year	Country	Educational level	Publication type/design	Population	Pedagogical strategy	Analytical method
21	Zolotov, 2002	Russia	n/s	Journal article	n/s	Symposia-based, full-analytical-cycle training	Quality assurance, metrology, chemometrics, IT
22	Masania et al., 2018	Western Europe (UK)	University	Journal article	Pharmacy students	Combined, iterative teaching model (theory + lab + digital tools + small groups)	n/s
23	Lanigan, 2008	USA	Undergraduate	Journal article	n/s	Pre-/post-laboratory group discussion	Instrumental analysis
24	Samide and Akinbo, 2008	USA	Undergraduate	Journal article	n/s	Thematically modular course organization	n/s
25	Wenzel, 2003	USA	n/s	Journal article	n/s	Cooperative work, complex laboratory projects	Modern instrumental methods
26	Streuli et al., 2025	Western Europe (Switzerland)	Undergraduate	Journal article	Undergraduate students	Substitution of traditional with green methods in lab courses	Green analytical chemistry
27	O'Haver, 1991	USA	n/s	Journal article	n/s	Computer-based learning tools	n/s
28	Otto and Wegscheider, 1990	Western Europe	n/s	Journal article	n/s	Computer-Based Analytical Chemistry (COBAC)	Chemometrics
29	Timmers et al., 2003	Western Europe (Belgium)	University (pharmaceutical faculty)	Journal article	Pharmaceutical students	ICT-supplemented classical instruction	n/s
30	Smagunova, 2004	Russia	University	Journal article	n/s	Limited/verified use of computer tools in metrology labs	Metrology
31	Inczédy, 1990	Western Europe	n/s	Journal article	n/s	Laboratory-robotics integration	Process analytical chemistry
32	Chauvel et al., 2002	USA	n/s	Journal article	n/s	Industry-academia collaboration (PAPAC materials/workshops)	Process analytical chemistry
33	Chernova and Kulapina, 2003	Russia	University (department account)	Journal article	n/s	Full-cycle research projects on real samples	Environmental/biological analysis
34	Longo et al., 2025	Eastern Europe (Brazil)	University	Journal article	Non-chemistry students	Problem-solving (PS) methodology	Quantitative/instrumental analysis, chromatography
35	Phillips, 2002	USA	n/s	Journal article	n/s	Comprehensive assessment (exam + lab + statistical analysis)	Mineral analysis
36	de Abreu et al., 2006	Eastern Europe (Brazil)	n/s	Journal article	n/s	Active, strategically designed methodological approaches	Qualitative analytical chemistry

(Continued)

TABLE 1 Continued

No.	Author/Year	Country	Educational level	Publication type/design	Population	Pedagogical strategy	Analytical method
37	Baiulescu and Stoica, 2003	Eastern Europe (Romania)	n/s	Journal article	n/s	Institutional development (access, mobility, infrastructure)	n/s
38	Hirsch, 1987	USA	n/s	Journal article (commentary)	n/s	Curriculum revision toward interdisciplinary objects	n/s
39	Dorokhova, 1987	Russia/USSR	n/s	Journal article (historical review)	n/s	n/s	n/s
40	Dvorkin, 2002	Russia	n/s	Journal article	n/s	n/s	Metrology
41	Engstrom, 1987	USA	n/s	Journal article (commentary)	n/s	n/s	n/s
42	Education and Teaching in Analytical Chemistry, 2003	Global/ international	n/s	Journal article (editorial)	n/s	International cooperation	n/s
43	Holme, 2023	USA	n/s	Journal article (editorial)	n/s	n/s	n/s
44	Hulanicki and Kemula, 1979	Eastern Europe (Poland)	University	Journal article	n/s	n/s	Separation methods, data processing, instrumental analysis
45	Betteridge, 1979	Western Europe (UK)	University	Journal article	n/s	n/s	n/s
46	Ellison and Hardcastle, 2019; Koel and Kaljurand, 2020	Global/ international	n/s	Journal article (2 sources combined in one entry — see note)	n/s	Shift toward data interpretation and interdisciplinary work	n/s
47	Bretz et al., 2022	USA	n/s	Journal article	n/s	Remote/virtual laboratories	n/s
48	Méndez et al., 2020	n/s	n/s	Journal article	n/s	Machine-learning/ chemometric integration	Chemometrics

Cells marked “n/s” indicate information not stated in the reviewed text; please verify these against the original source before submission. Figure 7 and the reference list are now consistent: both reflect the 48 sources that constitute the included studies for this review.

TABLE 2 PRISMA-ScR flow diagram: number of records identified, screened, excluded, and included.

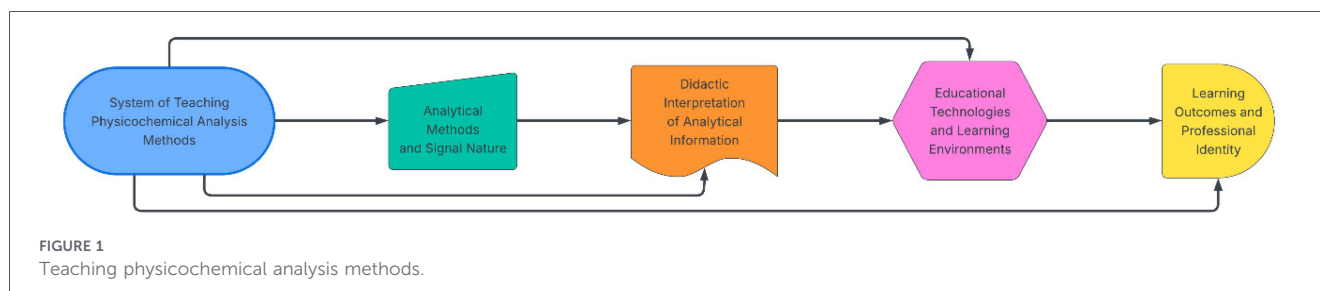
Stage (PRISMA-ScR)	<i>n</i>
Total unique records identified (Scopus, Web of Science, ScienceDirect, SpringerLink, ACS Publications, and RSCI/ eLIBRARY.ru, compiled in a single reference-management library)	<i>n</i> = 143
Records screened (title/abstract)	<i>n</i> = 143
Records excluded during screening	<i>n</i> = 95
Studies included in the review	<i>n</i> = 48

The search was compiled into a single reference-management library (Zotero) on 5 February 2026, drawing on Scopus, Web of Science, ScienceDirect, SpringerLink, ACS Publications, and RSCI (eLIBRARY.ru); duplicate records were resolved during compilation of the library, yielding 143 unique records for screening. Per-database record counts and the exact search strings used for each source were not retained in the exported library records and are not reported separately below.

education from which this core cannot be meaningfully separated. Where a cited source concerns analytical chemistry education more broadly, this is noted explicitly.

To clarify the conceptual logic of this review and the interrelations between analytical methods, didactic interpretation, educational technologies, and learning outcomes, a generalized framework of teaching physicochemical analysis methods is presented (Figure 1).

Structure of the review. Sections 3-9 report the results of the thematic synthesis, organized by conceptual/theoretical foundations, classification of methods, principles of system formation, implementation across educational levels, methodological approaches and technologies, digitalization, and development of professional competencies, each linked to one or more of the review questions RQ1-RQ6 (Section 2.3). Section 10 provides the Discussion, interpreting these results in relation to



the review questions, comparing them with the wider literature, and considering their educational implications and limitations. Section 11 presents the Conclusion.

2 Methods

2.1 Study design

This review was conducted as a scoping review following the methodological framework proposed for scoping studies and reported in accordance with the PRISMA Extension for Scoping Reviews (PRISMA-ScR). The scoping review approach was selected to comprehensively map key concepts, educational models, and methodological trends related to teaching physicochemical analysis methods, rather than to evaluate the effectiveness of specific interventions.

2.2 Information sources and search strategy

A comprehensive literature search was performed in major scientific databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, ACS Publications, and RSCI (eLIBRARY.ru). The search covered publications from 1975 to 2024 in English and Russian. The search strategy combined keywords related to analytical chemistry education and physicochemical analysis methods, including *analytical chemistry education*, *physicochemical analysis*, *teaching methods*, *problem-based learning*, *instrumental analysis*, *green analytical chemistry*, *chemometrics*, and *continuous chemical education*. Reference lists of relevant articles were also screened to identify additional sources.

Scopus and Web of Science were used as the primary bibliographic databases to identify the overall evidence base and to enable citation-based screening; ScienceDirect, SpringerLink, and ACS Publications were additionally searched as publisher platforms to capture full-text journal content, including items such as editorials and peer-reviewed commentaries, that are not always comprehensively indexed with abstracts in the bibliographic databases; RSCI (eLIBRARY.ru) was searched separately to capture the Russian-language literature. Records retrieved from the publisher platforms were compiled into the same reference-management library as the records from Scopus and Web of Science, and duplicates were resolved during this compilation.

The search was last run on 5 February 2026 and combined keyword and Boolean logic across title, abstract, and keyword fields, adapted to the syntax of each database.

2.3 Review questions

To guide the search, data extraction, and synthesis, this review addresses the following explicit review questions:

RQ1. Which pedagogical approaches (e.g., problem-based, research-oriented, cooperative, competency-based) are reported for teaching analytical chemistry and physicochemical analysis methods?

RQ2. Which competencies (conceptual, experimental, analytical-reasoning, metrological, digital, or professional) are targeted by these approaches?

RQ3. At which educational levels (secondary/pre-university, undergraduate, postgraduate, and continuing professional development) are these approaches implemented?

RQ4. Which digital tools and technologies are incorporated into teaching and learning, and how?

RQ5. What learning outcomes are reported or assessed in connection with these pedagogical approaches?

RQ6. What are the main gaps, limitations, and directions for further research identified in the literature?

2.4 Eligibility criteria

Publications were included if they: (I) addressed teaching or learning of analytical chemistry or physicochemical analysis methods; (II) discussed methodological, pedagogical, curricular, or conceptual aspects of education; (III) were peer-reviewed journal articles, conference papers, or authoritative reviews. Publications were excluded if they focused exclusively on technical analytical methods without educational context, or if they lacked relevance to teaching and learning processes.

Because the eligible literature spans general chemistry education, analytical-chemistry curricula, laboratory-specific pedagogy, and teacher professional development, conceptual heterogeneity was managed through the data-charting scheme (Section 2.6): each source was coded for educational level (secondary/pre-university, undergraduate, postgraduate, or continuing professional development, per the operational definition of continuous chemical education in Section 1) and for scope (curriculum-level versus laboratory/course-level intervention), so that studies addressing different levels or grain sizes could be compared within, rather than collapsed across,

these categories. Studies on general chemistry education were included only where the pedagogical content was explicitly framed around analytical or physicochemical methods; general chemistry-education studies without this focus were excluded under eligibility criterion (I) above.

2.5 Selection of sources

All identified records were screened in two stages. First, titles and abstracts were reviewed to assess relevance. Second, full-text screening was conducted for potentially eligible articles. Discrepancies were resolved through discussion. The selection process is summarized using a PRISMA-ScR flow diagram.

2.6 Data charting and synthesis

For each included source, key information was extracted, including publication year, country or region, educational level, analytical methods addressed, pedagogical approach, and primary educational focus. Extracted data were synthesized qualitatively to identify major thematic clusters and trends. A critical appraisal of individual sources was not performed, as the aim of this scoping review was to map concepts and approaches rather than assess evidence quality.

The thematic synthesis followed a hybrid coding approach: an initial set of codes was defined deductively from the review questions (RQ1-RQ6; Section 2.3) and the data-charting categories listed above, and additional codes were added inductively as recurring concepts emerged from the included sources during charting. Coded data were grouped into the higher-order thematic clusters that structure Sections 3–9 of this review (theoretical foundations, classification of methods, principles of system formation, implementation across educational levels, methodological approaches and technologies, digitalization, and development of professional competencies), each of which maps onto one or more of RQ1-RQ6. Coding and thematic charting were carried out by the review authors as part of the data-charting process described above.

Because no critical appraisal of study quality was performed, statements throughout this review that a pedagogical approach was “effective” or produced particular outcomes reflect what individual included studies reported, not an evidence-graded judgement by the present authors; such statements should be read as “the cited study reported favorable outcomes for...” rather than as a validated claim of effectiveness.

3 Theoretical foundations of physicochemical analysis as a component of chemical education

Analytical chemistry, in modern interpretations, is considered a multidimensional scientific and professional discipline, combining service, technological and fundamental components, and playing a key role not only in providing measurement information, but also in the formation of the professional identity of the analyst (Kissinger, 1992). In this regard, the goals

of teaching analytical chemistry are shifting from the formal mastery of methods to the development of analytical thinking, understanding of the principles of measurement and awareness of the role of analysis in solving scientific and practical problems (Pungor, 1981). The modern content of the discipline should reflect the priority areas of analytical science, including the development of sorption-spectroscopic and extraction methods, the theory of the action of organic reagents, molecular modeling of coordination compounds, as well as high-performance chromatographic and supercritical fluid technologies (Zolotov, 2000). Conceptualization of analysis as a process of extracting and interpreting information, in which the sample is considered as a unity of matter and information, justifies the need to include elements of systems analysis and information theory in training (Malissa, 1981). Taken together, these provisions confirm the advisability of considering analytical chemistry as an independent educational and scientific discipline aimed at training specialists who possess not only professional knowledge and skills, but also social and environmental responsibility (Pungor and Kellner, 1988).

The general logic of the relationship between the goals, content and learning outcomes of analytical chemistry is presented in Figure 2.

4 Classification and didactic interpretation of methods of physicochemical analysis

This review examines analytical chemistry as a system of scientific knowledge and educational practices aimed at developing analytical thinking, professional identity, and the ability to make informed analytical decisions. This approach requires a shift from descriptive presentation of individual analytical methods to a didactically verified teaching structure in which key analytical concepts and categories are introduced systematically and consistently. It is on this basis that a methodological framework for teaching methods of physicochemical analysis in continuing chemical education is formed.

Experience with the early and systematic introduction of concepts of analytical properties into analytical chemistry courses demonstrates that developing students' understanding of basic analytical categories at the initial stages of training facilitates a deeper understanding of the fundamental principles of the discipline and leads to sustainable improvement in academic performance. This approach allows us to view analytical chemistry not as a collection of disparate methods, but as a holistic system for obtaining, processing, and interpreting analytical information, which is a fundamental condition for developing the analytical thinking of future specialists (Valcárcel and Ríos, 1997). A logical consequence of this concept is the need to rethink the classification of physicochemical analysis methods in the educational process. In a didactic context, the classification of analytical methods should serve not only a systematizing but also a methodological function, reflecting the goals of the analysis, the nature of the analytical task, and the cognitive processes developed in students. As Pungor (1981) emphasizes, the didactic classification of analytical methods should be based not only on the physical nature of the analytical signal but also on their

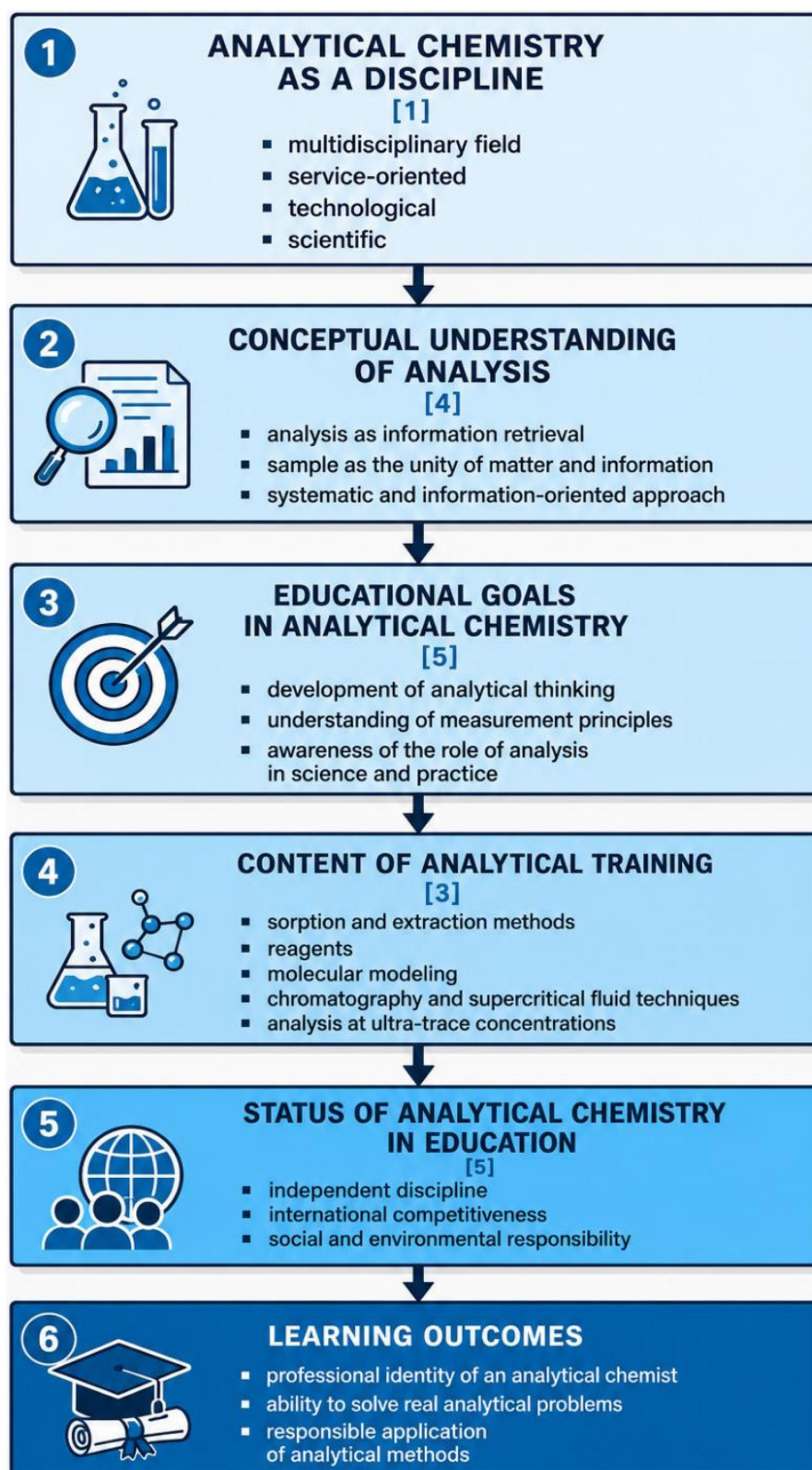


FIGURE 2

Conceptual model for the formation of a system for teaching methods of physical and chemical analysis based on the analysis of scientific and pedagogical sources.

TABLE 3 Sources and their contribution to the formation of elements of the conceptual model of learning.

No.	Source	Key characteristics extracted from the source	Elements of diagrams generated from the source
1	Valcárcel and Ríos (1997)	Analytical properties as fundamental concepts of the discipline; early and systematic introduction of key analytical concepts; the influence of concept structuring on the understanding of fundamental principles	Blocks reflecting basic analytical concepts and the logical sequence of their introduction in the educational system
2	Pungor (1981)	Goals of teaching analytical chemistry; developing analytical thinking; understanding the principles of measurement; the role of analytical chemistry in science and practice	Blocks of goal setting, educational objectives, and expected learning outcomes
3	Zolotov (2011)	The relationship between chemical equilibrium, analytical signal, and result; the need for a conscious systematization of methods; critique of the formal enumeration of methods	Blocks describing the structure of the analytical process and the interpretation of analytical results
4	Malissa (1987)	The analytical process as a holistic system; the stages of analysis (sample collection, sample preparation, measurement, data processing); didactic rethinking of traditional classifications	Blocks reflecting the functional stages of the analytical process and the logical organization of methods
5	Grasselli (1977)	Focusing training on real-world analytical tasks; the relationship of analytical methods with scientific and industrial practice; analytical logic of method selection	Blocks of practice-oriented application of methods and the contextual selection of analytical approaches
6	Burns (2002)	Integration of physical chemistry, instrumental analysis, and metrology; validation of analytical information; the evolution of analytical education	Summary blocks reflecting the integrity of analytical training and the interdisciplinary nature of the educational system

cognitive significance and role in the development of students' analytical thinking, including an understanding of the logic of method selection depending on the task at hand.

Developing this position, Zolotov (2011) points out that the systematization of analytical methods in educational courses should ensure a holistic understanding of the relationships between chemical equilibrium, the analytical signal, and the interpretation of analytical results. A formal listing of methods without disclosing their conceptual foundations reduces the educational value of the course and hinders the development of a holistic analytical worldview in students, focused on understanding the nature, limitations, and uncertainties of analytical measurements.

From a methodological perspective, this necessitates a transition from the traditional division of analytical methods into chemical and instrumental ones to a functionally oriented didactic model. Within this model, methods of physicochemical analysis are correlated with the stages of the analytical process—sampling, sample preparation, measurement, data processing, and interpretation—allowing for a direct connection between the educational material and real-world analytical tasks and professional practice (Malissa, 1987).

In modern educational concepts, such a classification is viewed as a tool for integrating the theoretical foundations of physical chemistry, instrumental analysis, and metrology into a unified didactic system. This approach helps students develop a holistic understanding of the processes of obtaining, evaluating, and validating analytical information and prepares them to solve scientific, technological, and socially significant problems, which meets modern requirements for the training of specialists in the field of analytical chemistry (Burns, 2002; Grasselli, 1977). The structuring of the didactic provisions underlying the construction of a conceptual model for teaching methods of

physicochemical analysis was carried out based on a comparative analysis of key publications, as well as the identification of characteristics used in the formation of elements of visual diagrams and models (Table 3).

5 Principles of formation of a system of teaching methods of physical and chemical analysis

5.1 Background and scope of the problem

The modern development of analytical chemistry as a scientific and educational discipline is characterized by its increasingly interdisciplinary nature and the expansion of the range of problems it addresses. Updated curricula in the natural sciences are increasingly focused on integrating knowledge from physics, biology, mathematics, computer science, and engineering, reflecting the real role of analytical chemistry in modern science and technology and requiring more comprehensive training for analysts (Otto, 2001). In this context, analytical chemistry is viewed as a deeply interdisciplinary field, historically and conceptually linked to the development of science, necessitating a rethinking of traditional approaches to its teaching (Stone, 2005).

5.2 Conceptual foundations of analytical chemistry education

According to several researchers, the development of a system for teaching methods of physicochemical analysis should be based on a systems-based and interdisciplinary approach, ensuring the

integration of theoretical foundations, experimental methods, and the interpretation of analytical information. This concept is considered a key condition for the modern training of analysts and is aimed at developing analytical thinking, not just mastering individual analytical techniques (Pungor, 1981). Within the framework of this approach, analysis is interpreted as a process of extracting and interpreting information, which requires the inclusion of elements of systems analysis and a conceptual understanding of measurements in the educational process (Malissa, 1987).

5.3 Curriculum design and continuity of education

Zolotov (2011) emphasizes that the principles of teaching analytical chemistry must adequately reflect the current state of the discipline and include updated course content, logical continuity between educational levels, and a focus on solving practice-oriented analytical problems. The formal transfer of established curricula without consideration of modern analytical challenges reduces the effectiveness of training specialists and limits their professional adaptability. In this regard, the importance of constructing educational trajectories that ensure a gradual transition from fundamental concepts to their practical implementation is emphasized.

5.4 Pedagogical strategies and learning outcomes

Several authors note that an effective system for teaching analytical chemistry should be based on the principles of continuity, problem-based learning, and the informed choice of analytical methods depending on the task at hand. This approach promotes the development of students' professional autonomy and the ability to apply analytical methods in real-world scientific and industrial situations (Grasselli, 1977). Contemporary pedagogical research also emphasizes the importance of combining fundamental theoretical training with active and research-based learning as the foundation of a sustainable educational model (Valcárcel, 2001).

5.5 Global trends and future directions

International reviews of analytical chemistry education emphasize that curriculum development must consider global scientific and technological trends, the development of instrumental methods, the digitalization of analytical control, and the need to train specialists capable of adapting to rapidly changing analytical challenges. These factors are considered crucial for the further evolution of educational strategies in analytical chemistry (Burns, 2002).

A systematization of evidence sources, their conceptual content, and the corresponding diagram types used in the analysis of educational approaches is presented in Table 4.

6 Implementation of continuous training in methods of physical and chemical analysis at various levels of education

6.1 Interdisciplinary coordination of analytical chemistry curricula

Current research emphasizes the need to revise the content of the analytical chemistry course based on targeted interdisciplinary coordination, particularly with physical chemistry. This approach involves eliminating duplicate and secondary topics and concentrating instructional time on fundamental and practically relevant analytical methods, which promotes a deeper understanding of the principles of analytical measurements and increases the effectiveness of the educational process (Vershinin, 2003).

6.2 Differentiation of basic and advanced analytical chemistry courses

An analysis of the structure of undergraduate and specialized courses in analytical chemistry shows that effective student training requires a clear distinction between basic and advanced disciplines. Furthermore, course content should be developed considering the students' theoretical background and current trends in analytical science, ensuring a gradual increase in the complexity of the material and logical continuity between educational levels (Sommer, 1993).

6.3 Continuing education and teacher professional development

A key element in the sustainable development of analytical chemistry education is the professional development of teachers. It has been shown that educational programs for teachers with various levels and profiles of training create conditions for the interdisciplinary exchange of experience and facilitate the development of skills for transferring scientific and educational approaches to school and university practice, thereby strengthening the integrative nature of chemical teaching (Calascibetta et al., 2000).

6.4 Practice-oriented models of professional training

Practice-oriented training models are reported to be associated with favorable outcomes in developing professional competencies. In the training system for medical laboratory technologists, analytical chemistry is integrated with clinical chemistry, the physical principles of analysis, and professional practice, while students' long-term work in educational and clinical laboratories ensures a strong connection between theoretical knowledge and real-world analytical tasks (Jacobsen, 1979).

TABLE 4 Sources of evidence and corresponding diagrams used in the review.

No.	Source	Presented data/concepts	Chart type	Connection to the review questions and objectives
1	Otto (2001)	Interdisciplinary curriculum structure; integration of physics, biology, mathematics, computer science, and engineering in analytical chemistry	Conceptual flowchart of interdisciplinary analyst training	Used to answer the question about interdisciplinary principles for developing a teaching system
2	Stone (2005)	Historical and conceptual role of analytical chemistry; impact of teaching approaches on student motivation and preparation	Diagram of the evolution of educational approaches	Supports the review's objective of rethinking pedagogical strategies
3	Pungor (1981)	Goals of analytical education; analytical thinking; principles of measurement	Diagram of "goals → content → learning outcomes"	Used to formalize the goal setting of the teaching system
4	Zolotov (2011)	Continuity of educational levels; connection between theory, experiment, and interpretation of results	Structural diagram of the analytical process	Answers the question about the systematicity and logical coherence of teaching
5	Malissa (1987)	Analysis as a process of information extraction; sample as the unity of matter and information	Philosophical and conceptual diagram of "analysis as an information process"	Used to substantiate the theoretical basis for teaching analytical methods
6	Grasselli (1977)	Real-world analytical tasks; choice of methods depending on the problem	Diagram of problem-based learning	Linked to the goal of developing practice-oriented analytical thinking
7	Burns (2002)	Global trends, instrumentalization, and digitalization of analytical chemistry	Summary diagram of the development of analytical education	Supports the review's objective of adapting teaching to modern challenges
8	Valcárcel (2001)	Integration of fundamental training and active learning	Systemic model of sustainable analytical education	Used to substantiate the sustainability and universality of the teaching system

7 Methodological approaches and educational technologies for teaching methods of physical and chemical analysis

Contemporary research in the teaching of analytical chemistry demonstrates a steady shift from traditional reproductive learning to active, integrative, and problem-oriented educational models. For example, testing a constructivist approach in a laboratory workshop on qualitative chemical analysis showed that the study of specific cation reactions, combined with the investigation of the underlying chemical phenomena, ensures effective acquisition of basic knowledge even in conditions of reduced class time and simultaneously leads to a significant reduction in the volume of laboratory waste ([Postigo et al., 2021](#)). In line with these trends, the need to integrate the principles of sustainable development and "green" analytical chemistry into the educational process is emphasized, focusing not only on the development of analytical methods, but also on the development of sustainable thinking in solving analytical problems, taking into account environmental, toxicological, and resource aspects ([Kurowska-Susdorf et al., 2019](#)). The importance of incorporating concepts of measurement uncertainty and modern pedagogical approaches, such as teamwork, the use of information technology, and virtual laboratories, into training has also been previously noted. This has led to the question of a possible shift in the educational paradigm toward more fundamental analytical training ([Chalmers, 1978](#)).

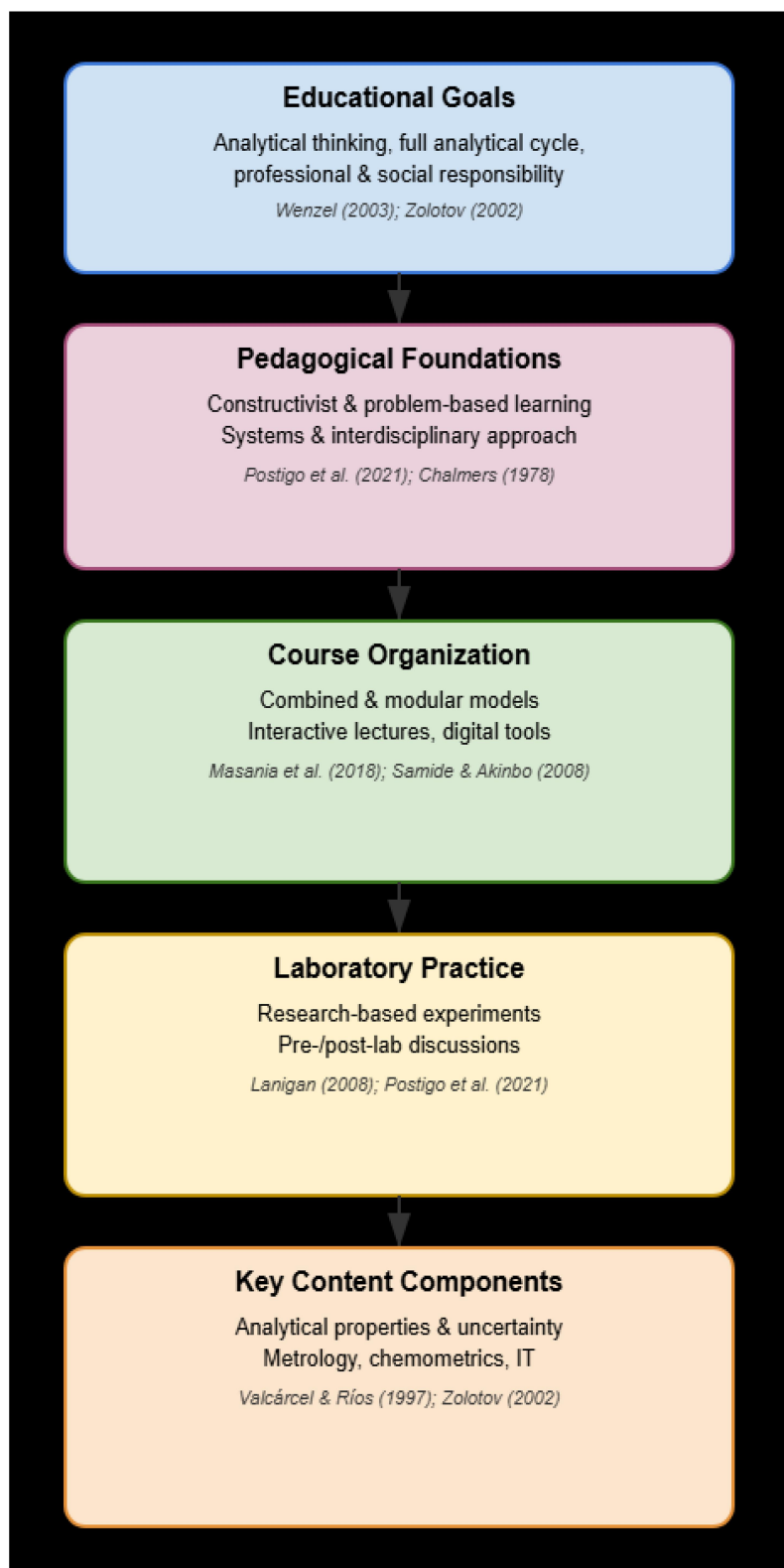
These ideas have been significantly developed in studies based on the materials of international symposia, which substantiate the feasibility of shifting the emphasis of training from the isolated

study of individual analytical methods to solving real-world analytical problems covering the full analytical cycle, including quality assurance, metrology, chemometrics, and the use of information technology ([Zolotov, 2002](#)). Favorable outcomes for this approach are reported in studies describing the implementation of combined educational models based on the organic integration of theory, laboratory practical training, interactive lectures, digital educational tools, and small group classes, which promotes sustainable knowledge acquisition, the development of analytical skills, and the active involvement of students in the educational process ([Masania et al., 2018](#)).

Similarly, it has been shown that adapting laboratory experiments with mandatory pre- and post-laboratory group discussions promotes the development of problem-solving skills and combines the advantages of inquiry-based and problem-based learning while maintaining the structure of the course ([Lanigan, 2008](#)). Thematically modular organization of laboratory courses, combined with a lecture component, is also considered an effective tool for integrating traditional and inquiry-based models of teaching analytical chemistry, ensuring high student motivation and increasing graduate employment ([Samide and Akinbo, 2008](#)).

In general, results-oriented learning, based on cooperative work and the implementation of complex laboratory projects using modern instrumental methods, contributes to the development of not only professional knowledge and skills but also key cross-curricular competencies necessary for modern analytical practice ([Wenzel, 2003](#)).

The hierarchical organization of goals, pedagogical foundations, course content and laboratory practice in the analyst training system is shown in [Figure 3](#).

**FIGURE 3**

Pedagogical model for the formation of a system for teaching methods of physical and chemical analysis based on the analysis of scientific and pedagogical sources.

8 Digitalization and innovative means of teaching physical and chemical analysis

Contemporary research in the field of teaching analytical chemistry emphasizes the increasing role of practice-oriented, digital, and environmentally responsible educational models. For example, it has been shown that integrating the principles of green analytical control and replacing traditional methods with environmentally friendly alternatives within undergraduate laboratory courses allows for the effective teaching of modern analytical methods while simultaneously reducing waste, costs, and risks, thereby strengthening the link between education and the principles of sustainable development (Streuli et al., 2025). A significant expansion of didactic opportunities for teaching analytical chemistry is also associated with the use of computer-based learning tools that provide students with interactive and dynamic work with quantitative models, simulations, and analytical tools unavailable in traditional textbooks and video materials (O'Haver, 1991). It is also emphasized that effective teaching of computer-oriented analytical control and chemometrics requires an integrated approach, including the use of specialized software, mastering the fundamentals of programming and logical analysis, as well as the presence of qualified teachers capable of providing interdisciplinary training for future analysts (Otto and Wegscheider, 1990). In pharmaceutical education, the introduction of information and communication technologies is considered an important factor in updating the educational process and increasing students' readiness for professional activity. However, it is emphasized that such technologies should complement, and not replace, classical academic forms of education (Timmers et al., 2003). At the same time, the advisability of a methodologically verified and limited use of computer tools in laboratory courses on metrology is substantiated, in which the primary manual processing of experimental data ensures a deep understanding of statistical methods, and software tools are used primarily for verifying and generalizing results (Smagunova, 2004). In the context of further technologization of analytical education, the principles of introducing laboratory robotics are considered, where the effectiveness of automated systems is determined by the quality of the development of chemical methods, the standardization of procedures, and the correct integration of equipment into the laboratory process (Inczédy, 1990). A significant contribution to the practice-oriented training of analysts is also made by the educational materials and workshops of PAPAC, based on cooperation between academic institutions and industry, which promote the adaptation of modern analytical and chemometric methods to the educational process and the formation of an applied understanding of the use of analytical instrumentation in students (Chauvel et al., 2002).

The sequential structure of the development of analyst competencies - from educational goals to automation and interaction with industry - is shown in Figure 4.

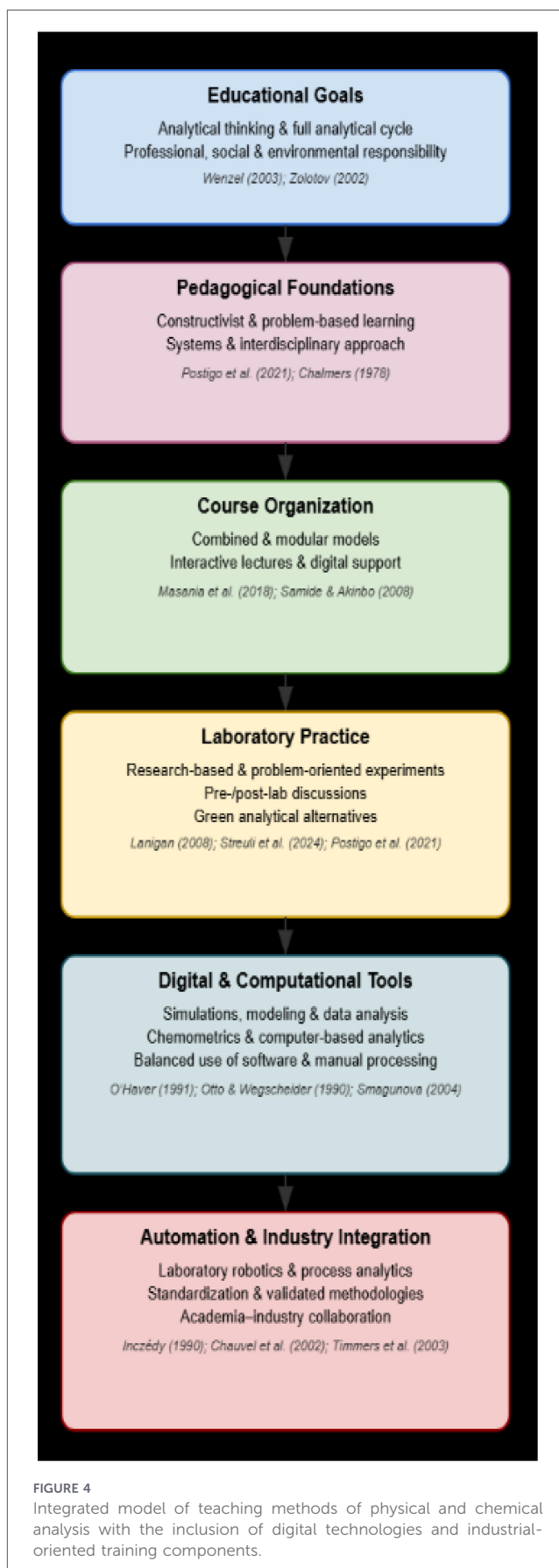


FIGURE 4

Integrated model of teaching methods of physical and chemical analysis with the inclusion of digital technologies and industrial-oriented training components.

9 Development of professional and research competencies of students

Modern pedagogical research highlights favorable outcomes associated with incorporating students' independent research activities into the teaching of analytical chemistry. It has been shown that completing educational research projects covering the full cycle of analytical measurement of real environmental and biological objects—from sampling to interpretation of results—significantly increases the awareness of the assimilation of analytical methods and promotes the formation of a holistic understanding of the structure and interrelations of analytical disciplines (Chernova and Kulapina, 2003). A significant development of these approaches is demonstrated by the application of problem-solving (PS) methodology in the teaching of quantitative and instrumental analytical chemistry, which provides a deeper understanding of sample preparation and chromatographic analysis methods, the development of practical skills, and the formation of a critical attitude toward the socio-ecological aspects of analytical activity, in particular, the problem of pesticide use (Longo et al., 2025). An additional element in improving the quality of training analysts is the introduction of comprehensive assessment systems that combine a theoretical exam, laboratory work and statistical analysis of experimental data, which allows not only to objectively assess the level of knowledge and skills of students, but also to develop sustainable practical skills, analytical thinking and readiness for professional activity in the applied areas of analytical chemistry (Phillips, 2002).

Across the studies discussed in this review, the relationship between learning theory, teaching strategy, student activity, expected outcome, and assessment method can be traced explicitly. Constructivist and inquiry-based learning underpin strategies that place students in direct contact with real analytical problems and ambiguous data, with the corresponding student activity being sample-to-result problem-solving and the expected outcome being deeper conceptual understanding of the analytical signal, assessed through open-ended laboratory reports or oral defense of results rather than recall-based testing. Cooperative and problem-based learning underpin strategies

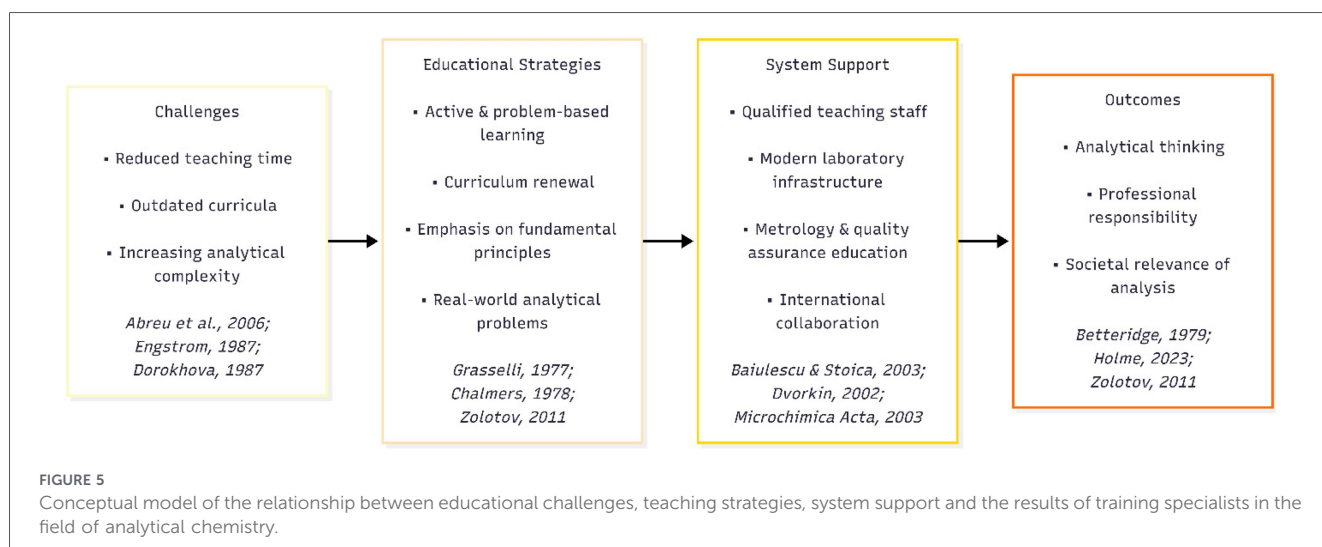
built around small-group laboratory projects, with the corresponding activity being collaborative planning and division of analytical tasks, the expected outcome being teamwork and professional-communication competence, assessed through peer- and instructor-rated group performance. Competency-based approaches underpin strategies that make explicit, assessable learning outcomes (e.g., correct method selection, uncertainty estimation) the organizing unit of the course, with assessment built around demonstrated performance against those outcomes rather than course completion alone. Making this chain explicit for each pedagogical strategy discussed in Sections 5–9, rather than treating constructivism, cooperative learning, problem-based learning, inquiry-based learning, and competency-based approaches as general labels, is intended to strengthen the theoretical grounding of the framework proposed in this review.

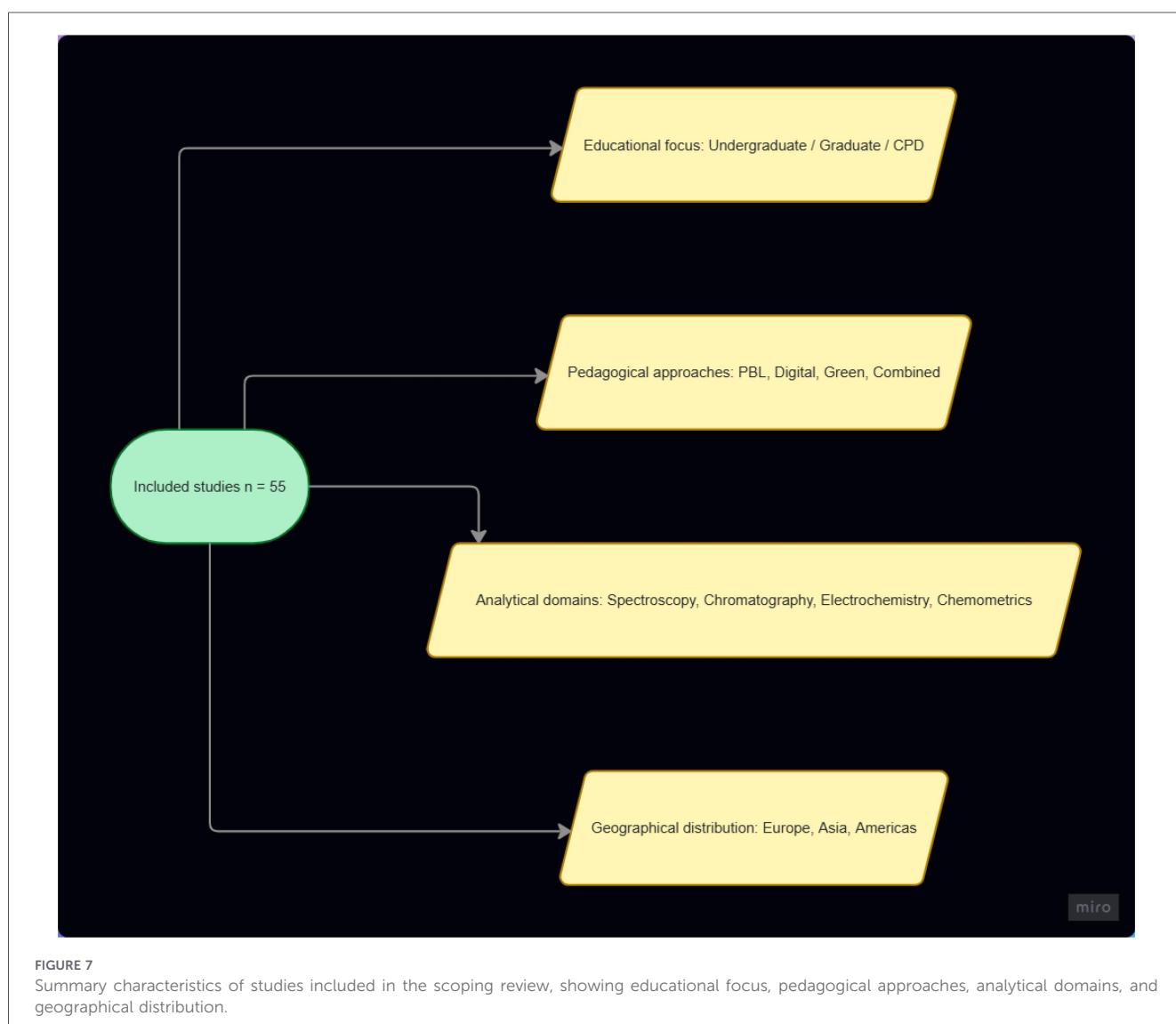
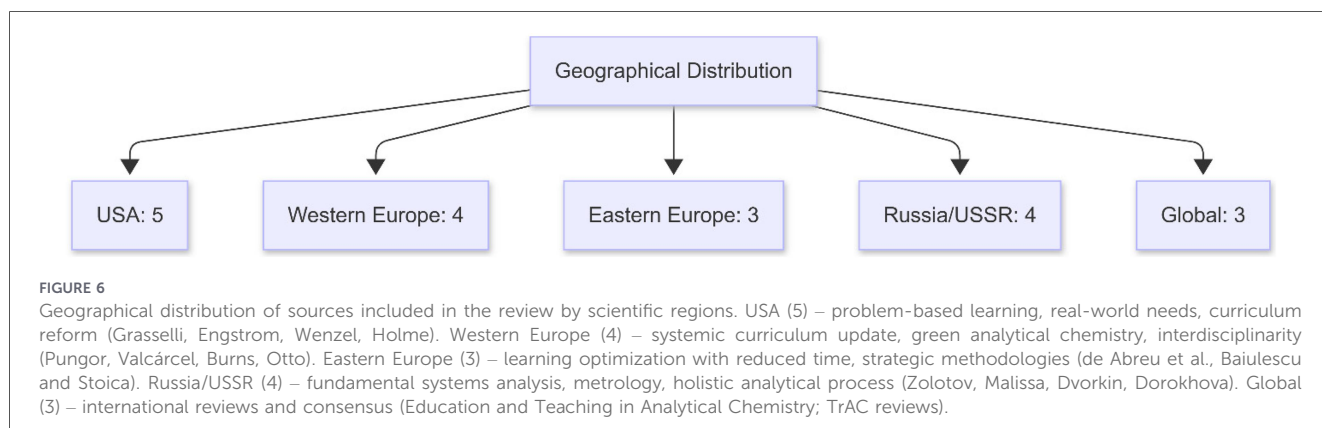
The learning outcomes and competencies discussed throughout this review can be grouped into the following non-exclusive categories: conceptual knowledge (understanding of analytical principles and method selection logic), experimental skills (laboratory technique and instrument operation), analytical reasoning (interpretation of data and troubleshooting), metrological competence (uncertainty estimation and quality assurance), statistical and data-interpretation skills, digital competencies (chemometrics, programming, use of laboratory software), sustainability awareness (green analytical chemistry principles), teamwork and communication, professional autonomy, and general professional preparedness.

The logic of the transition from the identified problems of teaching analytical chemistry to educational strategies, implementation conditions, and expected results of training analysts is shown in Figure 5.

10 Discussion: problems and prospects for the development of methods for teaching physical and chemical analysis

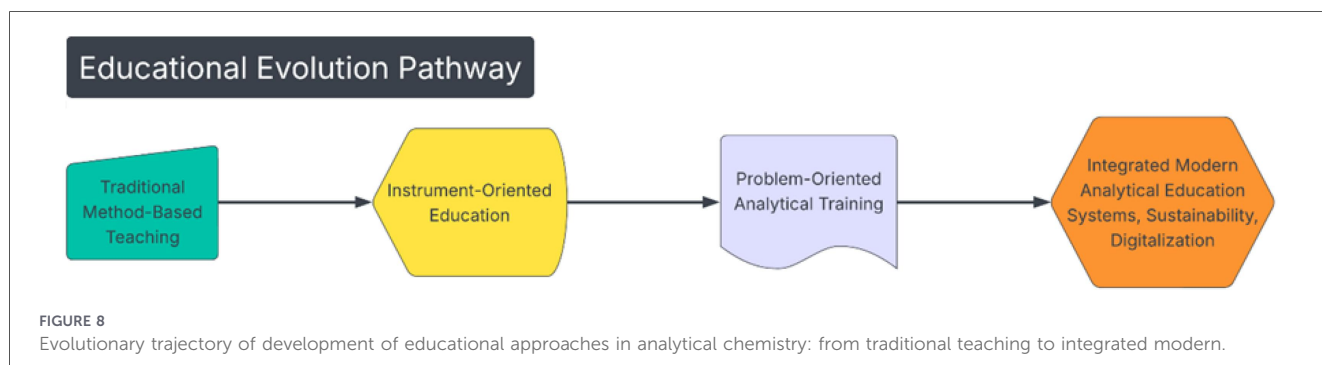
Note on the conceptual figures (Figures 2, 4, 5, 6, and 7). These figures represent successive, partially overlapping attempts





to depict the same underlying relationship between educational goals, content, pedagogical strategy, and learning outcomes, viewed through different lenses (didactic classification, digital/industrial integration, professional-competency development, and historical evolution, respectively). A possible consolidated

structure, offered here as an editorial proposal for the authors to adopt, adapt, or discard, would organize these five figures' content into a single four-layer model: (1) educational goals and challenges (from Figures 2, 6), (2) pedagogical foundations and strategies (from Figures 2, 4, and 6), (3) course organization,



technologies, and system support (from Figures 4, 5, and 6), and (4) learning outcomes and professional-competency development (from Figures 5, 6, and 7), with the historical evolution currently shown in Figure 8 retained as a separate, smaller supporting figure since it conveys a timeline rather than a structural relationship. This proposed consolidation is an editorial synthesis of the figures' existing content, not an independently derived or expert-validated model; as documented in Tables 3, 4, each element of these figures is traceable to specific characteristics extracted from individual charted sources; the model is therefore inductively derived from the charted literature rather than adapted from a single pre-existing educational model or independently validated by expert review. Its curricular usefulness should accordingly be presented as a proposal grounded in the literature, pending separate validation (e.g., expert review or pilot implementation), as already noted in the Conclusion.

Optimization of the teaching of high-quality analytical chemistry in the context of reduced class time, demonstrating that the introduction of active and strategically designed methodological approaches promotes the development of critical thinking, professional responsibility, and the effectiveness of the educational process in students and teachers (de Abreu et al., 2006). This result is logically complemented by the need for institutional changes, including expanded access to scientific information, academic mobility, and the development of modern laboratory infrastructure (Baiulescu and Stoica, 2003). In this regard, a revision of the content of the basic course in analytical chemistry is justified, focusing on complex interdisciplinary objects and systems that go beyond traditional instrumental analysis (Hirsch, 1987).

Summarized studies of the state of teaching demonstrate the systemic nature of methodological problems and the need for their conceptual rethinking (Dorokhova, 1987). Metrological training and quality assurance of analysis are becoming an essential component of modernization (Dvorkin, 2002), which is consistent with the priority of updating the content and methodology of teaching in accordance with the modern challenges of analytical science and practice (Zolotov, 2011). Such changes are reported to be reinforced by the use of a reflective and discussion-based pedagogical approach (Chalmers, 1978). As a result, the balance between fundamental principles, laboratory skills, and modern analytical technologies in specialist training is being updated (Engstrom, 1987). The practice-oriented focus of training ensures the connection of the

educational process with the real-world challenges of science and industry (Grasselli, 1977). Further development of the system presupposes international cooperation and constant adaptation to scientific and technological progress (Education and Teaching in Analytical Chemistry, 2003), which is confirmed by historical and analytical reviews of educational trends (Holme, 2023).

Thus, analytical education is viewed as a dynamic system requiring constant updating of content, an enhanced role for separation methods, data processing, and instrumental analysis (Hulanicki and Kemula, 1979), as well as a focus on fundamental measurement principles and the social significance of analytical chemistry (Betteridge, 1979).

The regional structure of publications included in the review, reflecting the international nature of research in the field of teaching analytical chemistry, is shown in Figure 6.

The regional breakdown above accounts for 19 of the 48 included studies; a country of origin could not be reliably identified from the source record alone for the remaining sources, which are therefore omitted from Figure 6 rather than misattributed. The same applies to Figure 9: category frequencies do not sum to 48 because a single study could be counted under more than one educational-component category.

The evolution of teaching approaches in analytical chemistry, from traditional method-centred instruction to integrated, problem-oriented and sustainability-driven education, is summarized in Figure 8.

The evolutionary model of educational approaches presented in Figure 8 reflects the transition from method-oriented learning to integrated training of analysts. However, modern research shows that this transformation is accompanied by a change in the very paradigm of analytical education. Training specialists is increasingly focused on developing the ability to interpret data, work with complex systems, and apply interdisciplinary knowledge, rather than solely on mastering instrumental techniques (Ellison and Hardcastle, 2019; Koel and Kaljurand, 2020). This is consistent with the broader observation that when theoretical instruction and laboratory practice are structurally separated, laboratory work tends to become procedural rather than conceptual, with students following instructions and generating data without engaging with why particular techniques, parameters, or decisions matter; models that integrate pre-laboratory conceptual preparation with decision-making during the practical session, including AI-supported flipped-laboratory formats, have been proposed specifically to

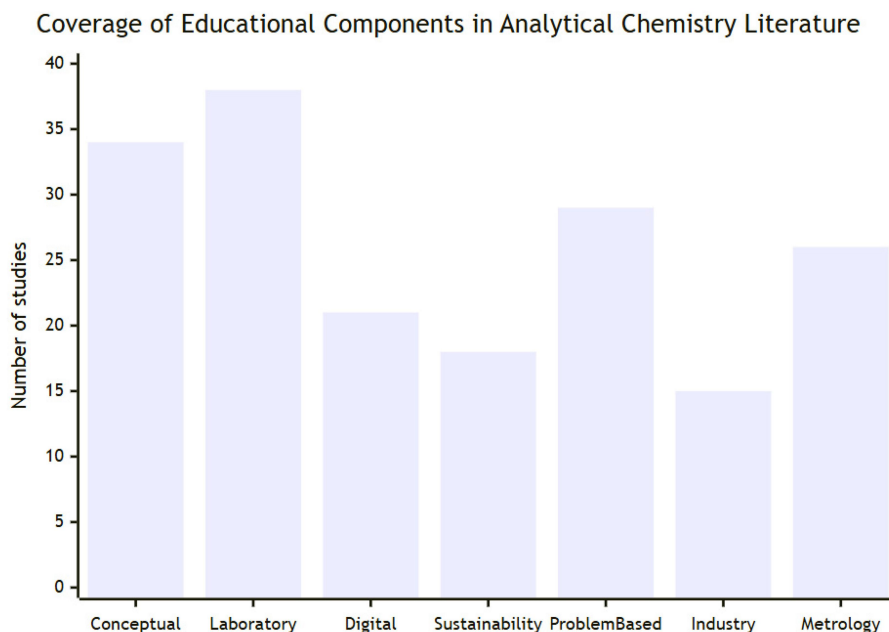


FIGURE 9
Coverage of educational components in analytical chemistry literature.

shift this balance back toward conceptual integration in analytical chemistry teaching (Correia et al., 2025).

The digitalization of analytical chemistry is a key factor in modernization. Modern educational practices include remote laboratories, virtual simulations, and the processing of large sets of experimental data, which has become particularly noticeable during the COVID-19 pandemic (Bretz et al., 2022). Furthermore, the introduction of machine learning and chemometric approaches creates new requirements for analyst training, including proficiency in statistical modeling and data analysis (Méndez et al., 2020).

Consequently, while Figure 8 demonstrates the conceptual evolution of pedagogical models, Figure 9 reflects its empirical confirmation: the distribution of studies shows the dominance of interdisciplinary, research-based, and digital forms of education, as well as the global nature of the modernization of specialist training. Taken together, this indicates a shift in analytics education from teaching methods to teaching how to work with analytical information.

11 Conclusion

This review systematizes and analyses scientific and methodological approaches to teaching physicochemical analysis methods in the context of continuing chemical education. The reviewed literature suggests that the evolution of analytical chemistry as a scientific and educational discipline is accompanied by a shift in emphasis from the isolated mastery of individual analytical techniques to the development of holistic analytical thinking based on an understanding of the nature of the analytical signal, the logic of method selection, the interpretation of results, and their metrological support. The reviewed studies suggest that the classification of

physicochemical analysis methods in the educational process should be based not only on the physical nature of the measurements but also on their didactic and educational value for the training of future analysts.

A summary of the literature suggests that the models most frequently reported as favorable for teaching analytical chemistry are characterized by the integration of theoretical foundations, laboratory practical training, problem-oriented and research-based assignments, as well as modern digital and information and communication technologies. Of particular importance is the inclusion of the full analytical cycle in the educational process—from problem formulation and sampling to data processing, uncertainty assessment, and results interpretation—which fosters students' professional autonomy and their readiness to solve real-world analytical problems.

Modern research places particular emphasis on the implementation of sustainable development principles and “green” analytical chemistry, which are viewed not only as a set of environmentally oriented methods but also as an important element in shaping the values and ethical attitudes of future specialists. In this context, analytical chemistry is not simply an instrumental discipline but a key component in training specialists who understand the social, environmental, and technological implications of analytical work.

At the same time, the analysis revealed several unresolved issues and areas for further research. These include the need for more precise didactic integration of chemometrics, big data processing, and artificial intelligence elements into educational programs, as well as the development of unified approaches to assessing learning outcomes in physicochemical analysis. Further development of interdisciplinary and modular educational models that ensure curriculum flexibility and adaptability to the rapidly changing requirements of analytical science and practice also appears to be a promising direction.

Thus, the review findings are consistent with modernizing the teaching of physicochemical analysis methods being a systemic and continuous process aimed at aligning course content, teaching methods, and educational outcomes with the current state of analytical chemistry. The presented synthesis can serve as a methodological basis for developing and improving analytical chemistry curricula at various levels of chemical education.

The integrated framework proposed in this review (Figures 2–7) should be understood as a conceptual synthesis derived from the mapped literature rather than as an empirically validated model; its practical usefulness for curriculum design will require dedicated validation, for example through expert review or pilot implementation. Because no critical appraisal of the quality of the included studies was performed, the trends summarized above describe what the reviewed literature most frequently reports rather than a quality-weighted judgement of which pedagogical strategies are most effective; establishing the latter would require a systematic review with formal quality and risk-of-bias assessment, which lies beyond the scope of the present scoping review.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

Author contributions

AT: Writing – review & editing, Methodology. KA: Formal analysis, Writing – review & editing. NZ: Writing – review & editing, Methodology. EN: Resources, Writing – review & editing. GB: Conceptualization, Writing – review & editing. AS: Visualization, Writing – review & editing. ZK: Methodology,

Writing – review & editing. NA: Writing – original draft, Formal analysis, Conceptualization, Validation.

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The author(s) declared that this research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

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