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Chemical Education Research

Design and Evaluation of an Innovative Pedagogical Strategy for Undergraduate Medical Students Learning Chemistry

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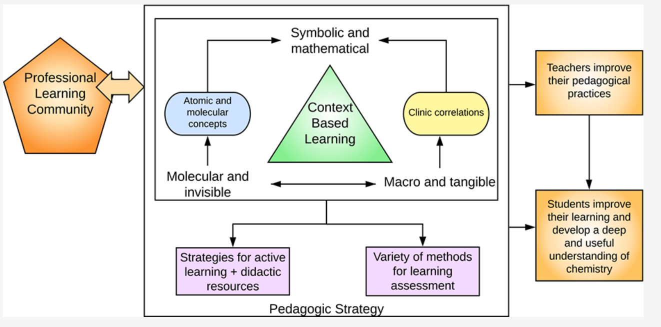
ABSTRACT: Training in chemistry is essential for undergraduate medical students; however, at the National University of Colombia, basic chemistry courses are associated with high fail rates and low academic performance with regard to first semester students, especially in vulnerable special admission populations. A longitudinal study was carried out via program evaluation methodology using quantitative and qualitative techniques to assess an innovative pedagogical strategy founded on context-based learning and different didactic and evaluative strategies employing information and communication technologies (ICT), which was tested on students of medicine by an interdisciplinary team of teachers in a new course. With the pedagogical strategy, a statistically significant improvement was observed in the academic performance of the students, with an increase in the mean grades that went from 3.61/5.00 to 3.95/5.00, a decrease of the fail rate from 15.50% to 3.48%, and the development of useful chemistry knowledge for the students during their training and for their professional lives. Furthermore, the study became an opportunity for collaborative learning among colleagues, favoring ongoing training of teaching staff and pedagogical innovation in professional learning communities.



KEYWORDS: *First-Year Undergraduate, Chemical Education Research, Context-Based Learning, Learning Theories, Professional Development*

Basic chemistry courses show high repeat and dropout rates in the first semesters of Ibero-American universities,[1−3] and in the case of USA educational institutes, they have become a barrier to those wanting to study science degrees.[4,5] The difficulty in learning chemistry at the university level has been related to factors associated with students, such as deficient foundations, a result of education received in high school,[6] the lack of motivation due to the low applicability they perceive chemistry to have in their profession,[7] and difficulties adapting to the university;[1] factors associated with educators, such as poor teacher training,[3] the lack of integration of contexts that relate chemistry to socio-cultural aspects or the everyday lives of students,[8] and the use of a specialized language in the teaching of nonchemists;[9,10] and curricular factors, such as the tendency of some universities to separate theoretical courses from practical ones reducing laboratory time[11] or the high level of abstraction required for the comprehension of some contents of the discipline.[1,7]

Furthermore, inequalities have been documented in academic results of basic chemical courses within STEM degrees that affect mainly women and ethnic and racial minorities,[12] and the negative experience in these courses is an important reason for why students decide not to continue a degree in the field of healthcare such as medicine.[13] In order to tackle the problem, educational institutions have in recent decades carried out curriculum reforms focused mainly on identifying and implementing practical teaching improvements that favor student learning, in two essential ways: (1) the reorientation of existing basic chemistry courses[14,15] and (2) the creation of new curricular paths.[16,17]

In relation to the second tendency, this work describes and evaluates a curriculum reform implemented at the National University of Colombia (UNAL), with the aim of reducing the failure rate in Basic Chemistry (BC), which gave rise to a new course: Basic Chemistry for Health Science (BCHS). This course was designed based on the ideas of Johnstone regarding the information processing model[10] and the chemistry triplet,[18] applying context-based learning, a methodological strategy in which concepts are applied in situations that are relevant for the

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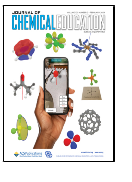

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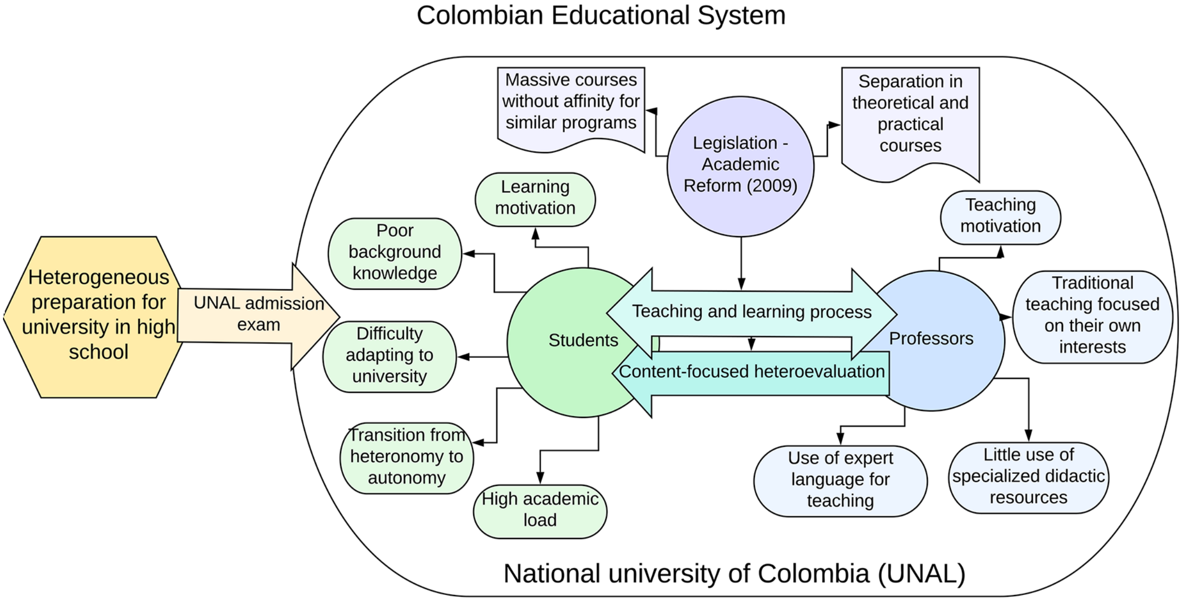

Figure 1. Diagnosis of the causes of a high failure rate in BC. "Diagram of problem causes" by Layton-Jaramillo, S. E.; Moncada, L. Chemistry tutoring: educational support program for health sciences students. *Rev. Fac. Med.* **2023**, *71* (4). DOI: 10.15446/revfacmed.v71n4.103876. Reprinted with permission from ref 26, under CC BY 3.0 Copyright 2023 Revista de la Facultad de Medicina.

students, generate interest and motivation toward the learning of science,[19] and promote meaningful learning and the development of argumentative[20] and problem solving skills.[21] Moreover, other elements considered were technological didactic resources and a wide range of assessment methods, and the importance of collaboration between teachers has been strengthened with professional learning communities (PLCs) on the horizon. PLCs are an educational innovation in themselves, as they are a way of reconfiguring educational institutions to promote change, educational improvement, and the professional development of teachers.[22] (See Annex 1 for details.)

■ PROJECT GOALS

The aims of the work are

1. To design and implement an innovative pedagogical strategy for a new basic chemistry course, which helps to reduce the fail rate and improve the academic performance of medical students.
2. To analyze the relationships between the characteristics of the new course and the academic results of the students, including additional measures on cognitive and affective aspects that favor learning.
3. To identify the relationship between the application of the pedagogical strategy and the development of a particular piece of chemistry knowledge that has been useful for the students during their training and in their professional lives.

■ METHODS

A program evaluation type study was carried out in four phases: diagnosis, intervention proposal, intervention, and intervention evaluation. The research design was longitudinal, orientated toward decision-making, employing quantitative and qualitative data collection instruments.

Context and Research Phases

In Colombia, the study of medicine involves an undergraduate course that lasts 6 years. At the UNAL, the curricular structure in the first three years forecasts a combination of basic sciences (including chemistry) and basic medical sciences; the fourth and fifth years involve rotations in formal clinical sciences, and in the final year, students undertake their practical medical experience via internships and their final dissertations.[23]

In 2009, the UNAL implemented an academic reform that sought a more in-depth application of interdisciplinary learning,[24] through which basic science courses were transformed. With the reform, the Basic Chemistry (BC) course was created, which began to be taught in a theoretical modality for groups of students from various careers (including medicine), distributed in about 20 heterogeneous groups, guided by different professors from the Department of Chemistry. Since its creation, the BC course has reported high fail rates;[25] this gave rise to this study, orientated toward the transformation of the problem. The period 2011 to 2013 saw the development of the first phase, in which the reasons for the high fail rate in BC were diagnosed,[26] the results of which are summarized in Figure 1.

With the diagnosis, the second phase of the study was implemented, which consisted of designing a pedagogical strategy for favoring chemistry learning. During the third phase, the proposal was implemented in a new course: Basic Chemistry of Health Science (BCHS), in which first semester medical students began to participate in 2014. The design and implementation of the teaching proposal was carried out by two of the authors of this article, professors of the Faculty of Medicine, a chemist and a physician, who through collaborative work shared their knowledge to improve the methods and strategies semester after semester. The fourth phase, carried out from 2014 to 2022, involved the evaluation of the curriculum reform of the course.

Description of the Pedagogical Strategy for the New Course

The new course was approved in Act 43 of December 05, 2013, by the Medical Faculty Council of the UNAL. It was designed under the context-based learning approach, structured through the articulation of teaching strategies and resources that favored learning in different settings (individual tasks, lectures classes,

Table 1. BCHS Curriculum (Context, Topics, and Clinical Correlations)

	Lecture (Coteaching)	
Context Research Papers for Reading (Preclass)	Topics	Clinic Correlations
Human body temperature regulation	Units of measurement and conversion factors	Drug administration
Diagnostic images and radiotherapy	Atomic structure	Diagnostic technologies
Necessary elements for living beings	Periodic table and periodic properties	Lithium drugs
Sickle cell anemia	Chemical bonding, intermolecular forces, and molecular geometry	Sickle cell anemia, CO poisoning, pulmonary surfactant
Homeopathy	Mol and Avogadro's number	Homeopathic medicine preparation
Isofluorano: a new general anesthetic for the 1980s	Properties of solids, liquids, and gases	Blood gases, anesthetic fluids
Fullerenes	Organic nomenclature and selected organic reactions	Reactions of the organic functions in the living being
Omega-3 polyunsaturate fatty acids	Stereochemistry	Cis and trans fats, thalidomide in the 1960s
Physiology of body fluids	Solutions, concentration units, and colligative properties	Hyponatremia, LEV (ketogenic diet)
Alterations of acid−base equilibrium	Chemical equilibrium, acid−base equilibrium, buffer solutions	Respiratory and metabolic acidosis and alkalosis
Entropy and life	Thermodynamic laws	Bioenergetics: obesity
Nitrogen fixation and nitrogenase	Introduction to chemical kinetics	Enzymatic kinetics
Oxidative stress, diseases, and antioxidant treatments	Principles of oxidation−reduction; electrochemistry	Pacemaker cells, degenerative diseases
Sugar-sweetened drinks and abdominal obesity	Carbohydrates, basic contents of human diets	Lactose intolerance
Clinical importance of lipids	Lipids, cholesterol, and steroid structures	Clinical evaluation of lipids
Biomedical applications of collagen	Amino acids and proteins	Protein digestion and amino acid absorption
Nucleic acids in diet	Nucleosides, nucleotides, and nucleic acids	Mutations
Oncogenic signaling pathways in The Cancer Genome Atlas	Constitution of the cell membrane, lipid bilayer; introduction to intracellular signaling	Cancer diseases

and tutorials sessions in small groups). The study plan (Table 1) was organized by taking into consideration the needs of medical training, starting from the foundations, in order to favor the construction of knowledge in an organized manner, from the simple to the complex.

Following the context-based learning model, each subject is framed within a clinical context, which is introduced with prereading papers. The lecture classes are developed in the coteaching modality, a teaching collaboration strategy in which the class is given by two teachers: a chemist and a physician. Applying the chemistry triplet,[18] the chemistry concepts are addressed from the micro level and the clinical applications, from the macro level, with both using the symbolic level explained in a language for "non experts" (Figure 2), using different didactic resources such as online presentations, descriptive videos, molecular models, virtual laboratory, and the ChemSketch software.

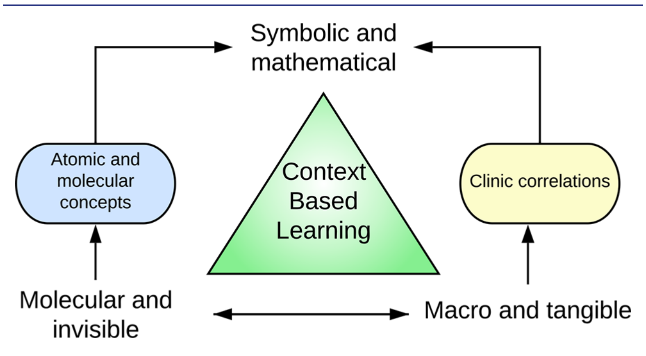

Figure 2. Schematic diagram for context-based learning applied in the chemistry triplet. Adapted from Johnstone, A. H. You Can't Get There from Here. *J. Chem. Educ.* **2010**, *87* (1), 22−29; DOI: 10.1021/ed800026d (ref 10). Copyright 2009 The American Chemical Society and Division of Chemical Education, Inc.

Following the class, the students carry out self-learning activities in the virtual classroom and are able to participate in voluntary tutorials in small groups to answer doubts. The learning evaluation process combines various methods (reading checks, independent tasks in LMS, and context-based exams). The BCHS exams are designed by the team of teachers involved in the course according to the content and learning objectives proposed for medical students. These were developed as context-based exams so that students must apply chemical knowledge to solve problems related to the practice of medicine. In this way, we expect students to continue learning while being assessed and to foster metacognition by highlighting the multiple connections between the two disciplines. Figure 3 shows a summary of the pedagogical strategy implemented in BCHS.

Courses, Population, and Sample

The population consists of students enrolled in the first semester of the UNAL Medicine program from 2009 to 2018, as summarized in Table 2.

The sample design was multistage, and the sample was changed according to the stage of the evaluation. The first stage involved determining the effect of the pedagogical strategy from the statistical analysis of BC and BCHS grades from 2009 to 2018, and the sample corresponded to 100% of the population.

In the second stage, the perception of students regarding BCHS was analyzed with a sample of 592 students from course 2 (47.93%), who responded voluntarily and anonymously to the comprehensive institutional teaching evaluation from 2014 to 2018.

For the third stage, there was an identification of those elements from the strategy that helped the students learn and the usefulness of the knowledge for training and professional life, with a sample of 322 students (26.07% from course 2), who responded voluntarily to a questionnaire applied in 2022, 128 (39.75%) women, 189 (58.70%) men, 3 (9.32×10^{-3}%) other,

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J. Chem. Educ. 2024, 101, 247−258

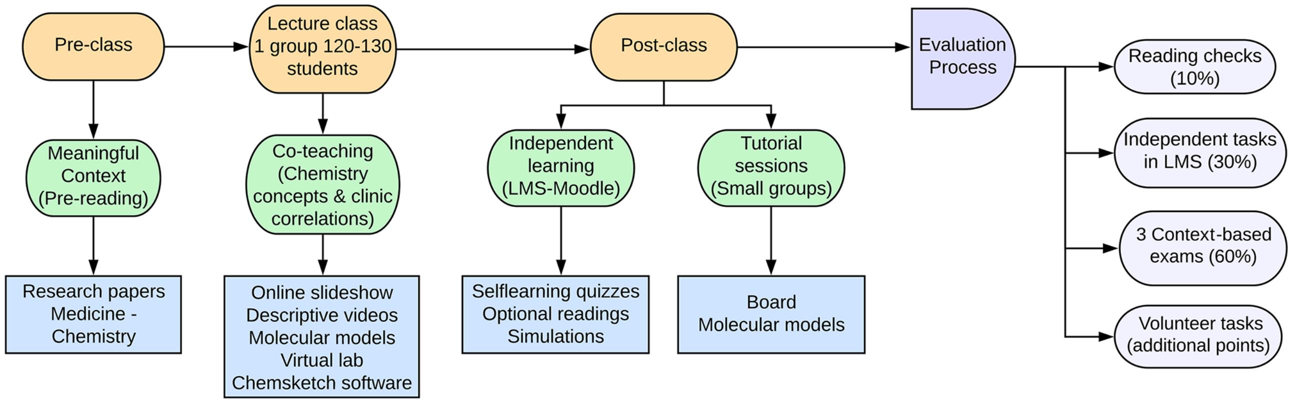

Figure 3. Pedagogical strategy implemented in BCHS.

Table 2. Population According to Course, Type of University Admission, and Gender

	Course 1 BC 2009−2013 (N = 1013)			Course 2 BCHS 2014−2018 (N = 1235)		
	N	%	Entry Score (Mean)	N	%	Entry Score (Mean)
According to Type of Admission[a]						
Regular admission	919	90.72%	782.43	1106	89.55%	779.75
Indigenous	28	2.76%	684.99	36	2.91%	696.70
Best high school certificate score	25	2.47%	764.19	46	3.72%	812.37
Poor municipality	24	2.37%	680.13	14	1.13%	682.63
Afro-Colombian population	17	1.68%	598.54	30	2.43%	618.82
Victims of armed conflict				3	0.24%	
According to Gender						
Women	355	35.04%	767.29	488	39.51%	767.42
Men	658	64.96%	777.20	747	60.49%	777.41

[a]In the UNAL, there is a quota of 150 places offered every semester for studying medicine, for which there are around 5000 candidates who are selected in accordance with their scores on the admission test. There are two types of intake: regular and special. The special admission program guarantees the intake of the best high school certificate score (in the country and poor municipalities) and ethnic minorities (Indigenous and Afro-Colombian population). As of 2016, with the Peace Agreement, a number of places were created for victims of armed conflict.

and 2 (6.21×10^{-3}%) who preferred not to state their gender, with an average age of 24.30, whose situation regarding the Medicine Program at the time the questionnaire was applied was as follows: 13 (4.04%) were on the whole studying basic subjects, 125 (38.82%) were on clinical rotations, 67 (20.81%) were on internships, 77 (23.91%) were working professionally, 9 (2.80%) were nonpracticing graduates, 24 (7.45%) were studying medicine in a postgraduate capacity, 5 (1.55%) did not continue with their studies, and 2 (6.21×10^{-3}%) had temporarily failed their medical degree.

Data Collection Instruments

Three data collection instruments were used in the study.

- Database with the entry score, type of admission and academic results for BC and BCHS, from 2009 to 2018, of medical students, provided by the UNAL Academic Information System. It is important to clarify that this database does not report the process by which each student obtained the final grade in BC or BCHS. However, since the authors of this article are the BCHS instructors and designers of the course exams, Table 3 shows, as an example, three exams administered in one semester. (See Annex 2 for details.)
- Comprehensive teaching evaluation applied by the UNAL.[27] Institutional instrument aimed at students, from which 8 questions were selected. (See Annex 3 for details.)

Table 3. Examples of Context-Based Exams in BCHS

Exam Link	Number of Students	Mean Grade	Cronbach's Alpha
First exam	133	3.2	0.82
Second exam	129	3.6	0.83
Final exam	132	3.1	0.78

- Perception questionnaire designed and validated during the study, organized in three blocks: socio-demographic data, elements that helped them to learn, and usefulness of learning. (See Annex 4 for details.)

Data Analysis

The statistical analysis of the quantitative data was carried out with the program SPSS v24, and the graphics were created in Excel. The percentage was calculated for the categorical variables and measures of central tendency for the descriptive analysis. The reliability of the BCHS exams was calculated by Cronbach's Alpha. For the inferential analysis, the Pearson and Mann−Whitney U nonparametric tests were used, given that the case of verified normality via the Shapiro−Wilk test ($p < 0.05$) and the case of homoscedasticity via the Levene test ($p < 0.05$) were not fulfilled. The qualitative data were processed with the Nvivo 2022 program, and the classification of the answers into categories and subcategories was carried out according to an inductive process.

Table 4. Mean Course Grades[a] and Fail Rate in BC and BCHS

	Basic Chemistry (BC)										
	2009−1	2009−2	2010−1	2010−2	2011−1	2011−2	2012−1	2012−2	2013−1	2013−2	Total
N	108	115	132	109	108	34[b]	75	114	114	104	**1013**
Mean grade	3.39	3.38	3.49	3.58	3.65	4.37	3.64	3.66	3.72	3.78	**3.61**
Fail rate (%)	**20.37**	**16.52**	**15.15**	**16.51**	**15.74**	**0.00**	**24.00**	**10.53**	**15.79**	**12.50**	**15.50**
	Basic Chemistry for Health Sciences (BCHS)										
	2014−1	2014−2	2015−1	2015−2	2016−1	2016−2	2017−1	2017−2	2018−1	2018−2	Total
N	126	134	120	128	117	122	119	128	124	117	**1235**
Mean grade	4.01	3.82	4.01	3.75	4.05	3.92	3.89	3.95	3.99	4.08	**3.95**
Fail rate (%)	**3.97**	**5.22**	**3.33**	**5.47**	**2.56**	**1.64**	**5.04**	**2.34**	**4.03**	**0.85**	**3.48**

[a]In Colombia, classifications are made on a scale from 0.0 to 5.0 and a pass is given for a grade equal to or higher than 3.0. [b]The second semester of 2011 was atypical, due to the protests of the Faculty of Medicine students, demanding a University Hospital. There were no new admittances in the first semester of 2012 to the program, and the 75 students reported are those who did not study BC the previous semester.

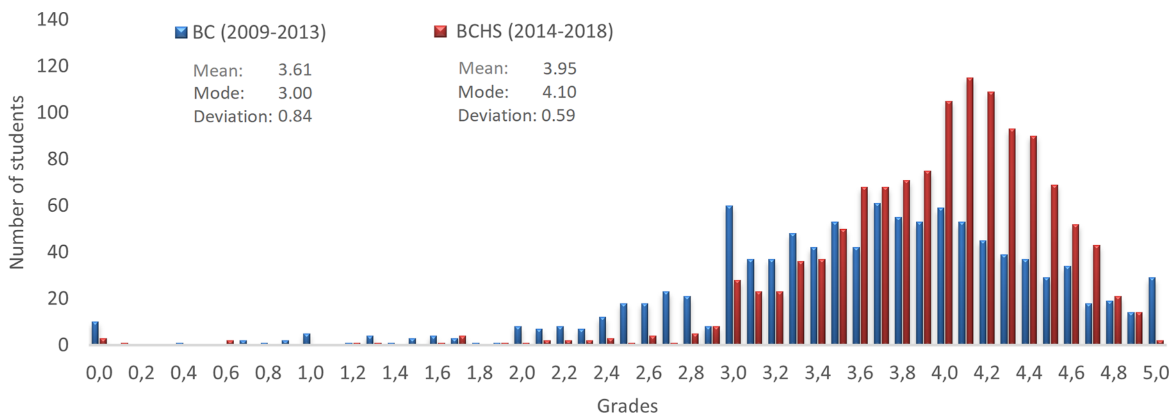

Figure 4. Frequency histogram of compared grades between the two subjects.

Table 5. Pearson Coefficient (x^2), Significance (p), and Fail Rate (%) in BC and BCHS[a]

Groups	Courses	Passed (*N*)	Not Passed (*N*)	x^2	*p*	Fail Rate (%)
Regular admission	BC	780	139	82.50	0.000	15.12%
	BCHS	1066	40			3.62%
Indigenous	BC	23	5	4.22	0.040	17.86%
	BCHS	35	1			2.78%
Best high school certificate	BC	23	2	3.79	0.052	8.00%
	BCHS	46	0			0.00%
Poor municipality	BC	19	5	3.36	0.067	20.83%
	BCHS	14	0			0.00%
Afro-Colombian	BC	11	28	6.30	0.012	35.29%
	BCHS	6	2			6.67%
Women	BC	301	54	48.48	0.000	15.21%
	BCHS	477	11			2.25%
Men	BC	555	103	52.07	0.000	15.65%
	BCHS	715	32			4.28%
Total	BC	856	157	99.15	0.000	15.50%
	BCHS	1192	43			3.48%

[a]Statistically significant to $p < 0.05$.

RESULTS

Statistical Analysis of Course Grades

Table 4 shows the mean grade and fail rate for BC from 2009 to 2013 and for BCHS from 2014 to 2018. In total, the failure rate dropped from 15.50% in BC to 3.48% in BCHS, and the mean grade improved, going from 3.61 to 3.95.

A comparison of the frequency histograms of grades between the two courses (Figure 4) reveals that in BCHS the academic results were better than in BC; the mean grade and mode are higher, and the standard deviation is lower.

Table 5 shows the results of the Pearson test and the failure rate in the two subjects according to the different population groups. The fail rate was lower in BCHS than in BC for all of the groups. The Pearson test indicates that the difference was statistically significant in the different groups, except in the best high school certificate group.

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J. Chem. Educ. 2024, 101, 247−258

Table 6. Mean Grade, U Mann-Whitney Test Outcome, and Effect Size (ES) for the Crossing of the Grades between BC and BCHS[a]

Groups	Courses	N	Mean Grade	σ	Z	p	ES
Regular admission	BC	919	3.61	0.853	−9.928	0.000	0.480
	BCHS	1106	3.94	0.589			
Indigenous	BC	28	3.43	0.693	−2.880	0.004	0.433
	BCHS	36	3.74	0.734			
Best high school certificate	BC	25	4.20	0.691	−0.229	0.818	0.118
	BCHS	46	4.26	0.376			
Poor municipality	BC	24	3.40	0.560	−2.677	0.007	1.059
	BCHS	14	3.91	0.295			
Afro-Colombian	BC	17	3.19	0.608	−3.148	0.002	0.970
	BCHS	30	3.77	0.592			
Women	BC	355	3.67	0.818	−6.194	0.000	0.483
	BCHS	488	3.99	0.522			
Men	BC	658	3.58	0.855	−8.993	0.000	0.445
	BCHS	747	3.91	0.625			
Total	BC	1033	3.61	0.862	−10.751	0.000	0.475
	BCHS	1235	3.95	0.588			

[a]Statistically significant to $p < 0.05$.

Table 6 shows the results of the nonparametric Mann−Whitney U test regarding the average grade from the two courses, which indicate statistically significant differences for all of the groups, except, once again, for the best high school certificate group. The effect size of the pedagogical strategy was high for the poor municipality group and the Afro-Colombian population and average for the rest of the groups, with the exception of best high school certificate and poor municipality, for whom the effect was low.

In the special admission groups, there is a trend in the entry score among those who studied BC and BCHS: the best high school certificates have higher than average entry scores, whereas in the case of indigenous, poor municipalities, and Afro-Colombians, entry tends to be below the average scores. For the former, those who studied BC entered with an average score of 764.19; they obtained a mean subject grade of 4.20, and the fail rate was 8.00%. Conversely, those who studied BCHS had a higher entry score (812.37) and a better mean grade (4.26) and none failed the subject. The differences are not, however, statistically significant; thus, these students acquired chemistry foundations in high school, sufficient to study the subject at the university with good results, independent of the course methodology.

At the other extreme are vulnerable groups such as students from poor municipalities and the Afro-Colombian population, who originate from schools with scarce resources and enter the university with low admission scores. For these groups, the BCHS pedagogical strategy had a high effect on grade improvements, and the differences between means were statistically significant, going from 3.40 to 3.91 in the case of students from poor municipalities ($p = 0.007$) and from 3.19 to 3.77 for the Afro-Colombian population ($p = 0.002$). For the indigenous student group, the entry score was 696.70 for those studying BCHS and 684.99 for those who studied BC. Although those with better scores obtained a better grade in chemistry (3.74 vs 3.43) and a lower fail rate (17.86% vs 2.78%), the differences were significant ($p = 0.004$), and the pedagogical strategy had an average effect on the academic results of this student group.

In regard to gender, the average scores for entry into the UNAL for those who studied BC and those who studied BCHS are very similar: 767.29 and 767.42 for women and 777.19 and 777.41 for men, respectively. Following the implementation of the pedagogical strategy, there was a drop in the fail rate and a statistically significant improvement in the academic results for both genders ($p = 0.000$).

Comprehensive Institutional Teaching Evaluation

The second stage of the evaluation involved analysis of the results of the institutional teaching evaluation for the BCHS course, from 2014 to 2018, to include additional measures on cognitive and affective aspects that favor learning.

For the question, *What was the aspect that most impacted you or the main teaching strength that helped you learn in the academic activities?*, the answers of 180 out of the 592 participants were classified into the chemistry-medicine-contextualization category, for example: "All of the classes are related to the approach of our degree". In this category, there was some associated context with motivation for learning, such as "The relationship the teacher makes between the subjects dealt with and topics that we shall look at in more detail in the future, which provides motivation for further study on these topics".

In contrast, for 102 participants, teaching attitude was the main aspect that helped them learn, and they made statements such as "They always answered the questions in the best way possible and with the best attitude". Another 86 students registered answers that were classified into the content knowledge (CK) category, for example: "Extensive knowledge of the subjects"; for 71 participants, what helped them to learn was the pedagogical content knowledge (PCK), a category in which statements were classified such as "The way in which they explain the topics is comprehensible and they make learning so much easier".

The answers from 14 participants were categorized as discourse recontextualization, for example: "Ability to speak in simple terms about complex things"; another 10 stated that the main teaching strength was development of autonomous learning, a category in which they mentioned, for example: "They give considerable encouragement toward the search for autonomous study".

Although only 10 answers were classified in the last category, in the dichotomous question: *Did the teacher encourage the*

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J. Chem. Educ. 2024, 101, 247−258

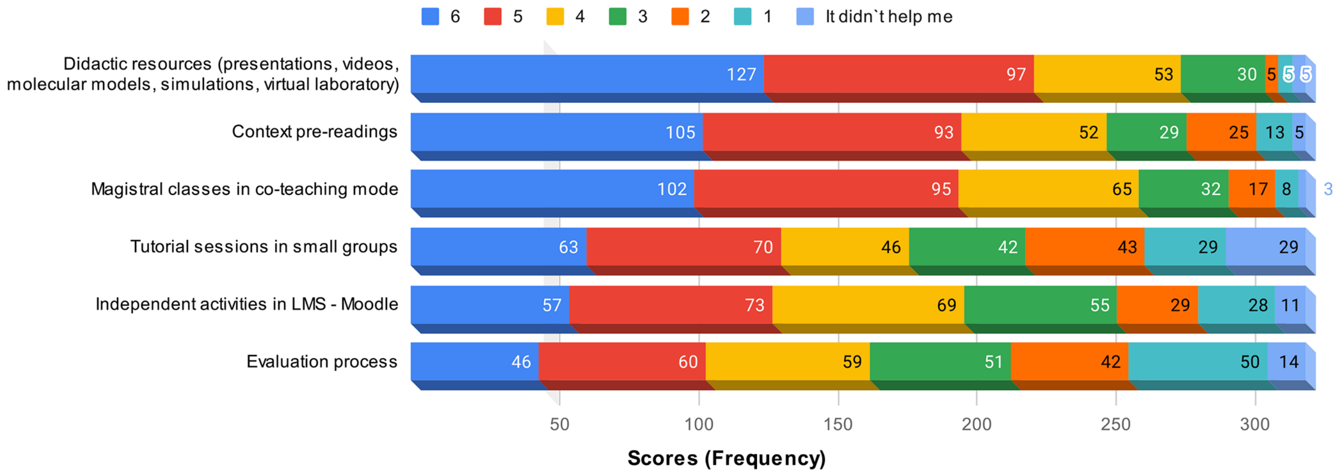

Figure 5. Frequency of each score for the different elements of the BCHS pedagogical proposal.

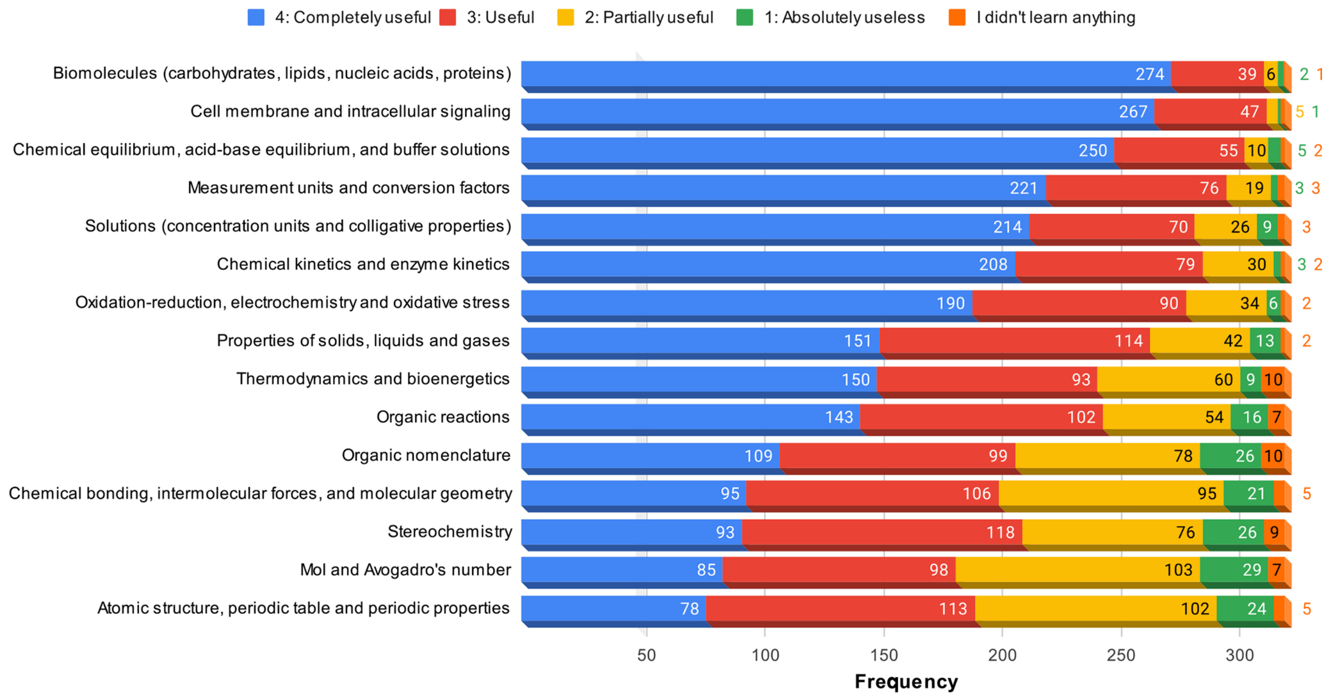

Figure 6. Frequency for each value of the Likert scale in each topic of BCHS.

acquisition of different tools for your autonomous learning?, 515 students (87.00%) answered yes and 77 (13.00%) answered no. In other words, the majority recognized that the BCHS pedagogical strategy helped them boost their learning autonomy, but very few considered this as a teaching strength.

The question, *Did the teacher contribute to you finding connections between the topics studied and other contexts or with other content from your study plan?*, was answered in the affirmative by 581 (98.09%) participants. This result is particularly relevant, taking into account that the BCHS pedagogical strategy is founded on context-based learning and is directly related to another two dichotomous questions: *Did you learn with the teacher what was dealt with in the academic activities in a sufficient and in-depth manner?* (which was answered in the affirmative by 87.59% (519 students)); *Did the teacher encourage in you argumentation or critical reflection?* (to which 91.43% (541 students) answered yes).

Regarding the affective aspects that favor learning, two dichotomous questions were selected: *Did the teacher inspire or motivate your interest in the topics studied? Did the teacher transform your way of thinking, feeling, or acting in relation to the subject(s) or activity(ies) taken with him?* The first was answered in the affirmative by 537 students (90.73%), and the second was answered likewise by 484 (81.68%).

For the last question, *Did the subject evaluations lead you to improve your learning?*, the answers were as follows: 76.24% Always, 18.92% Frequently, 4.16% Sometimes, and 0.68% Never. This result is especially relevant since the BCHS context-based exams intended for students to continue learning while being assessed.

Perception Questionnaire

In regard to the third objective, the questionnaire identified the elements of the pedagogical strategy that helped the students to learn (Figure 5) and the usefulness of the knowledge acquired in BCHS for training and professional life.

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J. Chem. Educ. 2024, 101, 247−258

The elements of the pedagogical strategy that contributed the most to learning, according to the participants, were the didactic resources (127), followed by the context prereadings (105) and the lectures classes (102). Nevertheless, the last element was the one that was the least frequent in the *It didn't help me box*, as only three participants indicated that the classes in the coteaching modality failed to contribute anything to their learning.

On the other hand, the tutorial sessions obtained the highest frequency in the *It didn't help me box*, 29 in total, although 69 gave this element a score of 6, indicating that for them this was the element that most helped them learn. The elements with a lower frequency of a score of 6 were independent activities in Moodle (57) and the evaluation process (46), but for those who selected them, these two elements were the ones that most helped them to learn.

Figure 6 shows the results on how useful they found what they learned in each of the BCHS topics for studying other subjects during their training.

All of the BCHS topics obtained more than 50% when adding the frequency of the values 4 (completely useful) and 3 (useful); the nonselection of value 1 (absolutely useless) or I didn't learn did not exceed 12% and 4%, respectively, for any topic.

Figure 7 shows the words most used in the answers to the question: How has the BCHS learning help you (or how did it help you) during your training? To which just one student answered negatively ("Very little"), whereas 313 mainly indicated that the BCHS learning helped them as a foundation for understanding more complex content in other areas of medicine.

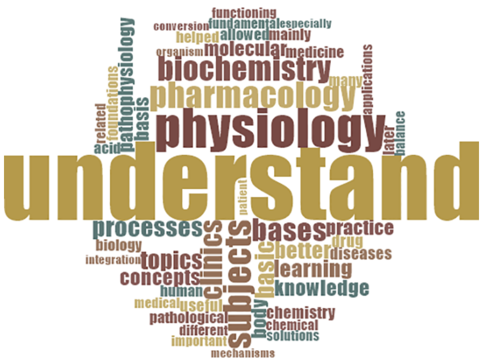

Figure 7. Word map for the answers to the question: How has the BCHS learning help you (or how did it help you) during your training in medicine?

The verb understand was the term most used to answer the question, as it appears in 212 entries (65.83%), for example: "In order to be able to understand and thus learn subsequent concepts more easily". In the same vein, the word basis was used 51 times (15.83%) to indicate that what was learned in BCHS provided the foundations for understanding and learning new contents, such as "To have bases [sic] for understanding through logic and not memory".

Related to the foregoing, words such as physiology 100 (31.06%), subjects 66 (20.50%), pharmacology 60 (18.63%), biochemistry 53 (16.46%), clinics 49 (15.22%), pathophysiology 27 (8.39%), molecular 26 (8.07%), and diseases 19 (5.90%) were also used to indicate the areas of knowledge in which BCHS learning was used, for example: "To understand subjects like pharmacology and physiology and in the future understand diseases and provide appropriate treatments".

Furthermore, the terms educational quality and high school were only used once but are relevant. One of the participants stated that BCHS helped him acquire the foundations of chemistry that he failed to acquire in high school: "They are the basis for understanding the degree in depth, especially for those of us who come from the far edges of the country where the education system did not teach such concepts"; conversely, another participant indicated that he had consolidated knowledge that he had acquired beforehand: "Consolidate knowledge I had brought from high school. To have a foundation sufficient to facilitate the understanding of biochemistry, physiology and pharmacology, among others".

For this question, it is important to draw attention to some answers that, despite not containing often used words, indicate that BCHS learning helped in the development of higher order thinking, for example: "Studying chemistry has allowed me to have a more analytical view of the material world, I've learned to think about both natural and laboratory phenomena from an energy perspective, understood as the consequence of possible and viable chemical interactions"; "To carry out a clinical correlation and focus on a patient from the most basic to the most comprehensive way".

Finally, Table 7 shows the responses to the noncompulsory question: Did what you learn in BCHS help you to solve problems in the practice of medicine? If the answer is yes, what one(s)?

Table 7. Categorization of the Answers on the Usefulness of Learning in BCHS to Solve Problems in the Practice of Medicine

Category	Frequency	Percentage
Pharmacology, prescription of medicines, and therapeutics	83	25.78
Arterial gases and alterations in acid−base balance	64	19.88
Solutions, administration of liquids, and electrolytes	40	12.42
Physiopathology: understanding of diseases and explanation to patients	37	11.49
Physiology: physical and chemical functions of human beings	15	4.66
Mechanisms of biomolecules in the organism	11	3.42
Nutrition, diet, and digestion	9	2.80
Interpretation of laboratory and paraclinical results	6	1.86
Enzymatic reactions	4	1.24
Oxidation−reduction processes	2	0.62
Energy processes and obesity	1	0.31
Anesthesiology	1	0.31
Renal patients	1	0.31

In this case, only the answers from 302 participants, who throughout 2022 were on clinical rotations or internships or had already graduated, were taken into account. Of these, 125 students were on clinical rotations, and 61.60% answered the question in the affirmative, with examples such as "Yes, it helped me with interpreting arterial gases, to identify if it's acidosis, of metabolic or respiratory origin for example or to understand what happens when a patient is in a state of hypoperfusion".

67 participants were on internships, and 67.16 answered affirmatively, citing examples including: "A great deal, from pharmacological situations with patients to the physiopathology of shock, it's extremely applicable".

The last group comprises those participants who have already graduated from the Medicine program, in three conditions: 77 graduates practicing the profession, 9 nonpracticing graduates,

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J. Chem. Educ. 2024, 101, 247−258

and 24 graduates studying postgraduate medicine. The question was answered affirmatively by, respectively, 70.13%, 44.44%, and 70.83%, with examples such as "Yes, it has helped me to differentiate between the properties of certain compounds and to avoid errors, for example, oxidative stress for knowing that administering a lot of oxygen is also bad for tissues".

In total, 197 of the 302 participants (65.23%) who had already had contact with the practice of medicine stated that the learning in BCHS was useful for solving problems related thereto.

DISCUSSION

The discussion has been structured according to three specific objectives.

Design and Implementation of an Innovative Pedagogical Strategy for a New Basic Chemistry Course

In the educational sphere, innovation involves planned and deliberate changes that seek the improvement of a situation susceptible to being improved; thus, it must be evaluated and scored in relation to its objectives.[28] The curriculum reform materialized with the pedagogical strategy designed and implemented in the BCHS subject transformed the problematic situation of high fail rates in BC, achieving the improvement of academic results for students of medicine, reflected overall in the increase in the mean grade, which went from 3.61 to 3.95, and the decrease of the percentage of students who failed the course, which went from 15.50% to 3.48%.

Relationships between the Course Characteristics and Academic Results

The results are coherent with the fact that the improvement in the academic results was promoted by the changes supposed by the introduction of the BCHS subject, in substitution of BC: the use of context-based learning strategies, the diversity of elements to encourage learning, and the introduction of different evaluation strategies.

Regarding the context-based learning approach, 98.09% of the students who responded to the comprehensive teaching evaluation between the years 2014 and 2018 stated that in BCHS they were able to find connections between the topics studied and other contexts or contents from their degree study plans, and for the open question on the aspect that most helped them to learn, the category with the highest frequency was chemistry-medicine contextualization, which some related to cognitive aspects and others to the motivation to learn. Regarding the affective aspects that favor learning, 90.73% stated that the teaching methodology motivated their interest in the topics studied, and for the cognitive aspects, 87.59% stated having learned that studied sufficiently and in depth and 91.43% indicated that they developed argumentative and critical reflection skills in BCHS. Correspondingly, in the questionnaire applied in 2022, the participants identified the context prereadings and the lecture classes in the coteaching modality, where the chemistry concepts were integrated with their clinical correlations, as elements that on the whole contributed to their learning. These results coincide with other studies in which, with the context-based learning approach, students are able to learn chemistry content sufficiently;[20,29] they develop both argumentative[19] and critical thinking[20] skills, and interest and motivation toward learning are favored.[19,30]

Regarding the integration of diverse teaching resources, another characteristics of the course, the questionnaire participants indicated that this was the element that contributed most to their learning, coinciding with studies that conclude that chemistry learning is favored with the use of specialized resources, such as molecular models,[31] explanatory videos,[32] simulations,[33,34] and virtual laboratories.[35−37] Thus, this study provides evidence of the importance of integrating traditional teaching with computer-based didactic methods in order to connect theory to practice in chemistry courses taught in a theoretical modality.

In any event, according to the questionnaire applied in 2022, each element of the pedagogical strategy helped the students in a different way, to the extent that what may be useful for the learning of some may not be useful for others, which is why it is important to diversify teaching strategies. According to Cano-García,[38] when learning, significant individual differences between students are detected, determined by their strengths and weaknesses, in such a way that the lack of opportunities for students to use their individual strengths in the learning process and for these strengths to be valued is a factor that leads to inequality.[12]

The pedagogical strategy implemented in BCHS led to statistically significant differences in grade improvements and fail rate decreases, in general, in the cases of both men and women. When detailing by type of admission to the university, it was found that the differences were statistically significant for students from vulnerable populations but not for the best high school certificate group. Thus, the reform especially benefitted those students who most needed it, helping them to raise their knowledge to the level of those who arrived at the university with better preparation in chemistry. Nevertheless, the standard deviation of grades in BCHS (0.59) was much lower than that in BC (0.84), and the grades are grouped into higher values, demonstrating that the pedagogical strategy helped the students from all of the groups to improve. These results coincide with studies that conclude that the incorporation of diverse teaching strategies that involve students more actively improve the academic results of all, decreasing inequality in basic science courses.[12]

The improvement of the academic results is also related to the different methods that comprise the evaluation process which, in accordance with 76.24% of the participants in the comprehensive teaching evaluation, always helped them to continue learning. When the assessment is carried out via a single method, as in BC, which mainly involved the application of a heteroevaluation based on rote contents,[26] students who are not very proficient for this type of evaluation are at a disadvantage, always obtaining the same negative results.[31] Coinciding with these results, recent studies[39] conclude that inequality in basic chemistry courses diminishes with the introduction of the diversification of assessment processes. Furthermore, according to Bortnik el al.,[40] context-based exams, such as those implemented in BCHS, favor the development of Higher Order Cognitive Skills (HOCS), improving students' academic outcomes.

Relationships between the Pedagogical Proposal and the Development of Useful Knowledge

The final objective required that a number of years had passed following the intervention for the BCHS students to advance in their degrees and professional practice. The findings indicate that all of the topics included in the study plan were useful, and the pedagogical strategy promoted the development of a coherent understanding of chemistry, which helped the students to understand concepts in other subjects during their training as physicians.

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J. Chem. Educ. 2024, 101, 247−258

This is how this study contributes elements for responding to concerns that, according to Cooper,[41] are of interest to CER researchers: What evidence do we have about how to help students develop a deep and robust understanding of chemistry? How will we know that students have developed a coherent and useful understanding of chemistry? The results allow it to be stated that, taking into account the principles of Johnstone's learning model[10] applied to BCHS, the students transformed the new information into knowledge and constructed support concepts that were stored in long-term memory, which were the anchor on which they constructed understandings of concepts at a greater level of complexity, in other knowledge areas such as physiology, pharmacology and biochemistry, as one participant stated: "(the learning in BCHS) were the bricks I used to build the knowledge I have now". Hence, it was important to construct the BCHS study plan from basic chemistry concepts, in such a way that those who had already acquired these foundations in preuniversity education reinforced their knowledge and those who had not acquired them had the opportunity to do so. This fact is especially relevant for ethnic minority students; as according to Chang et al.,[42] inequality in science training at the high school level affects the performance of these groups in science subjects at universities.

Regarding usefulness of knowledge, according to Cooper,[41] students should be able to apply chemistry learning to solving practical problems. The results indicate that with the foundations acquired in BCHS the students achieved a greater understanding of the problems of medical practice in order to make informed decisions, as expressed by a participant in the questionnaire: "Yes, especially affording meaning to the problems that arise on a daily basis in clinical practice and for the making of coherent and appropriate decisions in favor of the patient".

In accordance with Johnstone's information processing model, problem solving takes place in the long term memory, which can only hold a finite number of ideas.[10] The more complex a problem is, the greater is the number of operations that need to be carried out and the greater is the cognitive load, to which it is easier for an "expert" to solve complex problems than a "novice". The former use working memory more effectively because they are able to more easily access relevant concepts and skills in order to solve a specific problem.[43] With the BCHS pedagogical strategy, the students acquired knowledge that helped them to understand more advanced concepts in other subjects throughout their training and developed, without being aware of how, "expert" knowledge that allows them to solve complex problems in their practice of medicine, as described by one of the professionals who answered the questionnaire: "I have to admit that the learning, being a process, becomes 'blurry' at the exact moment of the acquisition of the skill or chain of thoughts used to solve a clinical problem; however, as an example I can state that the management of acid peptic and gastroesophageal reflux disease usually involves the use of pH controlling or neutralizing solutions, and having this chemistry knowledge is a fundamental basis for understanding the pharmacological mechanism by which substances like aluminum hydroxide act at the gastric level".

In this manner, with this study, there is also a contribution to another of the questions that is of interest to CER researchers: What should students know and be able to do with that knowledge?[41] (in this case, specifically for medical students).

CONCLUSIONS

The collaborative work between teachers in the PLC, facilitated the design and implementation of an innovative basic chemistry course, according to context-based learning, which involved the application of principles from the chemistry triplet, and information and communication technologies (ICT) was used in the development of diverse teaching strategies that favored active learning, along with the application of a number of evaluation methods. The BCHS pedagogical strategy achieved a decrease in the subject fail rate and an increase in mean grade scores, especially in relation to the most vulnerable groups; furthermore, the students developed a deep understanding of chemistry that was useful for their profession, as they recognized later from the perspective of practice, either for the comprehension and construction of knowledge in other subjects in the study plan or for solving problems in their professional careers.

LIMITATIONS

The main limitation of the study derives from the fact that the BC instructors are different from the instructors of the new subject, BCHS. Thus, all the pedagogical elements of the subject changed, so basically, the improvement in the students' academic results cannot be attributed entirely to the pedagogical strategy. On the other hand, according to the principle of teaching autonomy, professors are responsible for assessing their students' learning according to their own criteria, so the BC and BCHS exams were not the same. Thus, the study was based on the comparison between the final grades of both courses and not on the comparison of the process by which the students obtained those grades, in one or the other course.

IMPLICATIONS

The reduction in the fail rate in subjects for initial semesters, especially for the vulnerable population, has consequences at both the personal and institutional level. At a personal level, it means students are able to progress in their academic program and use chemistry learning to build knowledge in other more advanced subjects in the study plan. At the institutional level, it means an improvement in university management indicators, by avoiding the failure of subjects, university dropout, and waste of human and material resources.[44]

The improvement in academic performance in chemistry for medical students was promoted by the teamwork of the teachers who participated in the creation and implementation of the new course: a chemist and a physician, who contributed their CK, PCK, and technical knowledge (TK) to design the proposal and improve on it semester after semester, working on the basis of mutual respect, shared leadership, and the application of common values and principles in relation to teaching, learning, and evaluation.

In regards to CK, the dialogue between the two teachers, a chemist and a physician, permitted the design of significant contexts for each topic in the study plan, which is one of the key aspects for favoring both cognitive and affective aspects in the context-based learning approach.[20,40] For PCK, a type of knowledge necessary for teaching,[45] each contributed his experience, acquired in professional practice, for finding different ways of representing and formulating the topics and contents, with the purpose of them being understood by the students. For the students who responded to the questionnaire on teaching performance, the CK and the PKC of the BCHS

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J. Chem. Educ. 2024, 101, 247−258

teachers were main aspects that helped them learn, and in the 2022 questionnaire, the participants identified the teaching resources and lecture classes in the coteaching modality as elements that significantly contributed to their learning. The collaborative work between the BCHS teachers during the design and implementation of the pedagogical proposal not only was essential for the learning of the students but also became an opportunity for collaborative learning between colleagues through the exchange of practices, reflection, and research in the work context which, according to Bolivar,[46] is a privileged mechanism for favoring teacher training and pedagogical innovation in PLC.

Through collaborative work, the BCHS teachers improved their technological pedagogical content knowledge, knowledge that is achieved with the dynamic integration of CK, PK, and TK, which involves the understanding of how concepts can be represented using technology, how particular approaches can make use of particular technologies for teaching specific content, and how technology can be used to tackle what is difficult or easy to learn.[47] In this way, this study brings into evidence the importance of PLC in the development of the technological pedagogical content knowledge of teachers and the effective incorporation of technology for improving student learning.

The curriculum reform of a course can be carried out by a single teacher. However, when pedagogical transformations are managed by a community of teachers, the changes are maintained over time, better results are achieved, and teachers improve their pedagogical practices, contributing to the learning of the entire community.[48] According to Bolivar,[46] achieving better student learning requires the promotion of a learning culture in teachers, so that they get better at it every day. In this same sense, Bolam et al.[49] affirm that an effective PLC must have the capacity to promote and maintain the learning of its members, with the collective purpose of increasing student learning.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.3c00262.

Annex 1: Theoretical aspects for the design of the new course (PDF; DOCX)

Annex 2: Validity and reliability of BCHS context-based exams (PDF; DOCX)

Annex 3: Selected questions from the UNAL Teaching Evaluation (PDF; DOCX)

Annex 4: Perception questionnaire (PDF; DOCX)

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Notes

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