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Evidence of the Development of Pedagogical Content Knowledge of Chemistry Teachers about Redox Reactions in the Context of a Professional Development Program

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Abstract: In this study, we investigated the impact of a continuing professional development program (CPD) on the development of pedagogical content knowledge (PCK) of chemistry teachers regarding the topic of redox reactions. For this purpose, a CPD program designed to develop teachers' PCK on redox reactions was examined. During the course, teachers were observed and their activities were analyzed. The data collected were based on responses to the CoRe instrument, lesson plans, vignettes, and audiovisual records of the CPD program. Qualitative thematic analysis was employed to analyze the data, focusing on the five components of PCK proposed by Park and Oliver. The results demonstrate that teachers, after participating in the continuing education program, were able to independently develop the components of PCK at different levels, with the knowledge of instructional strategies showing the most prominent improvement. Additionally, it was observed that the components could potentially be integrated, suggesting the potential for enhancing PCK in the context of redox reactions.

Keywords: chemistry education; pedagogical content knowledge; continuous professional development; redox reactions

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1. Introduction

Teacher knowledge is a crucial factor for effective teaching and student learning outcomes [1]. It encompasses a wide range of specialized domains of knowledge that educators must possess to convert subject matter knowledge into pedagogically efficient and adaptable formats in order to effectively engage students, facilitate learning, and promote academic success [2]. Among these forms of knowledge, the one specific to teachers in a particular subject area that has received significant attention in the field of education is pedagogical content knowledge (PCK). Consider a chemistry teacher who not only needs a deep understanding of chemical concepts but also the ability to translate this knowledge into engaging classroom experiences. For instance, when teaching redox reactions, the teacher may employ practical experiments, such as the construction of galvanic cells with and without the use of a salt bridge, which would address a common student misconception about the passage of electrons through the salt bridge. This knowledge can significantly affect students' comprehension and enthusiasm for the subject.

Shulman introduced the concept of pedagogical content knowledge as one of the foundational components of teaching. According to Shulman, PCK is the intersection of disciplinary knowledge (where most of the content knowledge comes from) and pedagogical knowledge (where most of the teaching knowledge comes from) [3,4]. Shulman's key idea was to bring teachers' knowledge in terms of specific content to the center of the discussion [5]. After all, a teacher is always a teacher of some content, and their pedagogical practice revolves around that content [4]. After Shulman's proposal [4], several authors have emphasized the importance of PCK [6,7].

Pedagogical content knowledge refers to teachers' understanding of how to effectively teach a specific subject to students [4,8]. It goes beyond mere content mastery and involves a deep understanding of how to engage students, address their misconceptions, and effectively deal with them [9,10].

For chemistry teachers, PCK involves not only a deep understanding of chemistry concepts, theories, and principles but also the ability to translate that knowledge into meaningful instructional experiences. This implies thinking about the content in its entirety for its teaching, selecting appropriate teaching strategies, designing relevant learning activities, and assessing students' progress to promote conceptual understanding and scientific thinking [11–13].

The development of PCK is a complex process influenced by the content to be taught, the context in which the content is taught, and the teachers' reflection on their teaching experiences [14]. Some sources of PCK development include teaching experience, reflection on teaching practices, professional development programs, and mentoring supervision. While it is widely accepted that PCK develops throughout a teacher's career along with teaching experience [15–17], teaching experience alone, in the absence of teachers' education programs, is not sufficient to develop teachers' PCK [18].

Considering that teaching experience supported by teacher education programs is important for PCK development, and that there are few studies in the literature that investigate potential changes in the PCK of in-service teachers during a professional development program [6], this study aims to answer the following research question: what are the observed changes in the pedagogical content knowledge (PCK) regarding redox reactions of in-service chemistry teachers following their participation in a continuing professional development program?

2. Theoretical Framework

For over three decades, there have been various models, definitions, and interpretations of what PCK is [13,16,19–24]. Despite the diversity, there is a consensus that PCK is one of the fundamental domains of knowledge required for the teaching profession [8]. Currently, PCK is widely regarded as one of the pillars of teacher knowledge [5,13,25], an essential requirement for competent teaching, encompassing both the knowledge and skills to teach a specific subject [7], a way of understanding the complex relationship between different knowledge components and how they are integrated [26].

While scholars have developed different models of PCK, there is also a consensus that PCK comprises multiple distinct elements that are integrated and function synergistically when applied to address practical challenges [8]. The model proposed by Magnusson et al. [16] and its variants have been the most commonly used PCK models in science education. For science teachers, PCK includes (i) orientation to teaching science, (ii) knowledge of students' understanding in science, (iii) knowledge of science curriculum, (iv) knowledge of instructional strategies for teaching science, and (v) knowledge of assessment of science learning [24].

This model stands out for its integration of the distinct components previously proposed; thus, the five components influence each other in a continuous and contextualized manner. This model represents its components in a pentagonal shape to highlight the interconnectedness between them, assigning equal importance to each interaction. According to the authors, an increase in one component without a corresponding increase in the others may not be sufficient to alter the structure of PCK. Park and Oliver [24] state that PCK for effective teaching is the integration of all aspects of teacher knowledge in highly complex ways. In addition to these characteristics, this model highlights the issue of reflection. According to the authors, the construct of PCK emphasizes that a teacher is not a mere technician, one who merely applies what others have planned. The teacher is capable of improving their practice, primarily through interaction with students and reflection in action and on action [27].

PCK models have implications for teacher education curricula as they can assist teacher educators in planning a curriculum aimed at more comprehensive teacher training. For this study, the pentagonal model of PCK will serve as a conceptual tool for data analysis and interpretation.

There is limited research in the literature that has investigated the influences of continuing education courses on science teachers' PCK. To create effective professional development programs, it is important to understand the nature of teachers' PCK, how it develops over time, and how it relates to other components of knowledge, such as general pedagogical knowledge and content knowledge [28]. Additionally, it is important to identify and provide effective models for reflecting on teaching practices given their particular importance for improving the integration of PCK components [27].

Regarding the teaching of content related to the concept of redox reactions, De Jong and Treagust [29] (p. 335) highlight the importance of teachers "developing their knowledge of students' alternative conceptions of electrochemical phenomena and the difficulties students have in understanding these phenomena". Many studies have focused on the difficulties students encounter in understanding concepts related to redox reactions [30–32].

Some common difficulties are based on a lack of understanding of electric current, electrical conductivity in solutions, representation of oxidation–reduction reactions, reduction potential, dependence between reduction reactions and oxidation reactions, electron transfer process, meaning of oxidation numbers, identification of reagents as oxidants and reducers, and balancing redox reactions. Additionally, several students are unable to differentiate reactions at the macroscopic level of substances from the submicroscopic level of particles [33].

Some studies on redox reactions have shown the imprecise and often inadequate language presented in textbooks to explain the concepts involved in redox reactions [30,34,35]. Another factor leading to alternative conceptions is the existence of various explanation models for this content. Sometimes, redox reactions are introduced from a historical perspective and therefore approached through different models. This use of multiple models can be confusing for some students as it focuses on alternative definitions, such as applying the oxygen-based definition of redox reactions to identify all redox processes.

Other studies have focused on teachers' PCK regarding redox reactions [36] and teaching strategies and practical activities involving redox reactions [37]. However, it is worth noting that studies on teachers' conceptions of redox reactions are still scarce [38,39]. What is known is that teachers generally face difficulties regarding pedagogical content knowledge, i.e., how to teach redox reactions. These difficulties may stem from gaps in their initial teacher education. In this regard, the importance of developing and providing continuing education courses to promote pedagogical content knowledge about redox reactions is emphasized.

3. Materials and Methods

The present study is characterized as qualitative research [40], focusing on investigating the PCK of chemistry teachers and how this knowledge can be developed.

3.1. Background

This study took place within the context of a continuing professional development program (CPD) conducted in partnership with the Institute of Chemistry of the University of São Paulo, and the São Paulo State Department of Education (SEESP), Brazil. The course had a duration of 40 h, divided into 6 weekly sessions of 5 h each, with an additional 10 h of distance activities conducted in a virtual learning environment. The objective of the course was to promote the professional development of high school chemistry teachers regarding the redox reactions concept.

To emphasize the components of PCK and deepen content knowledge, the CPD program was organized by topics related to galvanic cells, specifically redox reactions. Over the course of six weeks, the following topics were covered: (1) Teaching Redox Reactions; (2) Electrolytic Solutions; (3 and 4) Redox Reactions; (5) Salt Bridge; (6) The Role of Reflection in Practice.

The activities and discussions on redox reactions conducted throughout the CPD course were planned, based on the five components of PCK according to Park and Oliver [24], with an emphasis on knowledge of instructional strategies and understanding of students (Table 1). While these components were individually discussed, it is crucial to highlight that the intervention consistently emphasized the integration of these components. This was achieved by encouraging participants to reflect on how each component relates to and complements the others in real classroom scenarios. In addition to the PCK components, content knowledge was addressed throughout the discussions of electrochemistry concepts.

Table 1. Overview of the five PCK components covered during the CPD program.

PCK Components	Activities
Orientation to Teaching Science	Planning a lesson plan (LP), in which teachers wrote down their objectives and purposes for teaching galvanic cells and explained the reasons for these choices.
Knowledge of Science Curriculum	Identification and discussion of subordinate concepts corresponding to galvanic cells, from sequencing to learning, review of basic concepts needed before teaching galvanic cells.
Knowledge of Students' Understanding in Science	Presentation and discussion of widely reported alternative concepts and difficulties in the literature on electrochemistry.
Knowledge of Instructional Strategies for Teaching Science	The emphasis on specific rather than general pedagogical strategies. Discussion and awareness of selecting teaching strategies to address possible alternative conceptions.
Knowledge of Assessment of Science Learning	Discussion and awareness in selecting specific assessment methods, justifying how and when to use them.

3.2. Participants

Twenty in-service chemistry teachers who participated in the course comprised our research participants. These teachers were selected based on their attendance of all six face-to-face sessions and completion of all data collection activities. Among these teachers, ten had completed a postgraduate degree. Eighteen teachers held a degree in chemistry education and nine also held a bachelor's degree in chemistry. One participant held only a bachelor's degree in chemistry, and another had a degree in chemical engineering. Regarding their teaching positions, all participants taught at the high school level. Additionally, five of them also taught at the middle school level, and three taught at the technical level. All participants taught chemistry, two of them taught chemistry and science, another two taught chemistry and physics, and the remaining two taught chemistry and mathematics. In terms of experience, the majority of participants were experienced teachers with over 11 years of teaching experience [41]. All teachers worked in public institutions, with seven also teaching in private institutions.

3.3. Data Collection

Considering that the development of pedagogical content knowledge (PCK) is a complex process in which its components interact dynamically, diverse data collection methods were utilized to amass the maximum possible amount of data. The main instruments were used for data collection: (1) CoRe instrument, (2) produced materials: lessons plans, (3) vignettes, and (4) observation.

3.3.1. CoRe Instrument

The content representation instrument—CoRe—is a tool that focuses on the teacher's understanding of aspects representing specific content, such as strategies and methodologies [42]. It comprises eight questions regarding the teaching of a set of central ideas associated with specific content and can be conducted in a group or individually. The CoRe has been successfully used in science teacher training to assist them in comprehending what PCK may entail [38,43–45] and to help them focus on specific content and consider alternative approaches to their teaching planning [46].

In the context of this research, the participants filled out the CoRe individually, with each of them selecting the ideas they deemed most appropriate to the topic of redox reactions. The CoRe instrument was answered at the beginning (CoRe1) and end of the course (CoRe2).

3.3.2. Lesson Plans

Lesson plans have emerged as an important strategy for research on PCK [6,47] because they typically provide a description of lesson planning, including the strategies and materials to be used, types of assessment, and the justifications for these choices. The participants developed a lesson plan for the topic of redox reactions in the first course meeting (LP1), and, at the end of the course, they developed a new lesson plan (LP2).

3.3.3. Vignettes

In addition to the CoRe instrument, a questionnaire with four vignettes [48] was also used in the construction of the data. This questionnaire was answered in the fourth meeting of the CPD program as an activity. It was used with the purpose of stimulating reflection among participating teachers in specific classroom situations. Vignettes are a description of a problem situation; in some cases, they can be written; in other cases, they can be audiovisual representations, for example, of a classroom [49]. Vignettes have proven to be useful as a research tool in the investigation of pedagogical content knowledge [48–53]. The purpose of the vignettes used in this study was to get an idea about the teachers' PCK on redox reactions based on a classroom situation described in the vignette. For each vignette, teachers were asked to describe what they would do in that specific situation [48].

The first vignette presents an image with the reactivity series of metals and then depicts a classroom situation in which the student asks the teacher how to determine which element oxidizes and which one reduces when you have two noble metals from the same group. The second vignette deals with phenomena often described in textbooks, which is the reaction between metallic copper and silver nitrate. It describes a classroom situation where the teacher conducts a demonstration experiment. After the description, there is a brief dialogue between the teacher and the student about the blue color of the solution. In the third vignette, a demonstration experiment is also reported in which the teacher adds concentrated nitric acid to a copper coin. The students observe the formation of a brown gas and the blue coloration of the solution and ask the teacher why a chemical reaction occurred in this case. In the fourth vignette, the topic of redox reactions is addressed through the theme of iron and aluminum production. In this situation, the student asks the teacher why aluminum is more expensive than iron considering that it is more abundant.

The vignettes were elaborated to assess the five components of PCK, as well as content knowledge [48]. Since they address specific curriculum topics, this allows teachers to demonstrate their understanding of what should be taught (knowledge of science curriculum). Through teachers' answers to the vignettes, we can gain insights into their awareness of students' characteristics and needs (knowledge of students' understanding in science). By questioning teachers' actions in each situation, the vignettes explored teaching strategies, enabling us to identify how teachers planned and implemented instruction (knowledge of instructional strategies for teaching science). The vignettes, particularly the first and third, included scenarios related to assessing student learning, providing insights into how teachers measure progress and adapt their instruction based on assessment results (knowledge of assessment of science learning). Moreover, since they address practical teaching situations, it is possible to analyze the orientation to teaching science.

3.3.4. Observations

Observation is the process of gathering data by watching people and places in a research setting. The advantages of collecting data through observation are related to the opportunity to acquire information as it unfolds in a real-life environment, to study actual behavior, and to examine individuals who may have difficulty verbalizing their ideas. Observations are a valuable research tool in investigating pedagogical content knowledge (PCK) [2,54]. The six sessions of the continuing professional development course were observed and documented through audiovisual recordings.

3.4. Data Analysis

Data analysis involved qualitative thematic analysis [55]. The collected documents (CoRe, lesson plans, answers to the vignettes, transcription of CPD sessions, produced materials) were organized and grouped. The coding process primarily involved a combination of inductive and deductive approaches.

Initially, we began with an inductive coding strategy, allowing codes to emerge directly from the data themselves. This involved reading and re-reading the transcripts to identify recurring themes, patterns, and concepts that naturally emerged during our data immersion. For example, in the analysis of lesson plans, the inductive approach led to the emergence of codes like "difficulty of students", "use of experimentation", "how the content fits into the curriculum". These codes were created based on the patterns and concepts that appeared in the participants' responses without any preconceived categories.

However, we also employed a deductive approach, where the codes were grouped into themes, and the themes arose from the five components of PCK according to Park and Oliver [24]. In this manner, the codes were then grouped into five themes: (i) orientation to teaching science, (ii) knowledge of students' understanding in science, (iii) knowledge of science curriculum, (iv) knowledge of instructional strategies for teaching science, and (v) knowledge of assessment of science learning [24].

In this study, the choice to use this model was made because the primary focus is to predominantly examine the influence of PCK components on the development of this knowledge. Furthermore, the issue of reflection (reflection-in-action and reflection-on-action) [27], emphasized in the model, was addressed throughout the course, both in the readings and in the CoRe instrument and lesson plan.

To ensure the quality and reliability of our analyses, we employed a rigorous and systematic coding process that involved two researchers. The coding process involved an initial round of individual coding, followed by extensive discussions and consensus-building among the research team. This approach allowed us to cross-verify and validate the coding decisions, enhancing the overall quality of our analysis.

As the qualitative thematic analysis is not a linear process but moves back and forth throughout the process, even in the selection of vivid and convincing extract examples, a review of the specifics of each theme was carried out. Therefore, for the final analysis, the selected extracts were reviewed in accordance with the research question and the literature, yielding the analysis results presented in the next section.

4. Results and Discussion

The analysis of the participating teachers' knowledge was conducted using the five components of PCK as proposed by Park and Oliver [24]. In total, 756 coded segments were identified across all the analyzed documents. Of these, 335 segments were coded in the initial documents (CoRe1 and LP1), and 421 segments were coded in the final documents (CoRe2 and LP2). When comparing the codes from the beginning (335) to those at the end of the course (421), an increase in these manifestations related to the components of PCK was verified. Furthermore, through data analysis, it was possible to identify signs that the participants expressed that they had expanded their knowledge in all PCK components. However, merely observing the frequency of the components is not sufficient to determine whether there was development in the PCK components. It was expected that, with a CPD course, the teachers would show some improvement. What needs to be verified and analyzed is the quality of these manifestations. In this context, Abell [56] emphasizes the importance of establishing the relationship between PCK and teaching practice in terms of quality and quantity. According to Table 2, an increase in specific manifestations related to the content of redox reactions can be observed between the beginning and the end of the course.

Table 2. Overview of coding between specific and general components.

PCK Components	CoRe1 [1]	CoRe2 [2]	LP1 [3]	LP2 [4]
Teacher-centered Orientation	56	62	25	27
Student-centered Orientation	16	34	1	14
Learning Difficulties—General	42	29	-	-
Learning Difficulties—Specific	30	49	-	-
Strategies—General	54	33	14	9
Strategies—Specific	11	34	14	27
Assessment—General	60	60	1	7
Assessment—Specific	4	13	1	15

[1] Content representations answered at the beginning of the course. [2] Content representations answered at the end of the course. [3] Lesson plans prepared at the beginning of the course. [4] Lesson plans prepared at the end of the course.

It is worth noting that none of the lesson plans showed evidence of knowledge of difficulties and/or conceptions about redox reactions as these were only expressed in the responses to the CoRe instrument.

Next, evidence of the development of each component of the participants' PCK will be presented.

4.1. Orientation to Teaching Science

Orientation to teaching science encompasses the teacher's knowledge and beliefs about the purposes and goals of science teaching. It also includes the teacher's ideas about the nature of science teaching and learning. A starting point was regarding the importance of teaching redox reactions. Almost half of the teachers (11) considered teaching this content very important, four teachers considered it extremely essential, and five considered it important. No teacher considered it unimportant.

According to the data analysis, 235 segments were coded as orientation, with 98 segments coded in documents related to the beginning of the course, and 137 segments coded in documents related to the final part of the course. The CoRe instrument was the instrument with which more identifications of orientation were completed. In this sense, the course contributes to teachers explicitly stating their teaching objectives.

Although teacher-centered orientations still prevail, there was an increase in manifestations related to student-centered orientation at the end of the course. In Table 3, it can be specifically observed which types of orientation were expressed by the teachers throughout the course.

Didactics and academic rigor are teacher-centered orientations [57]. The most expressed orientation by the teachers was didactics, in which the teachers aim to transmit scientific facts:

> Explain that the aluminum process is more expensive. (P1, Vignette)
>
> Explain what oxidation/reduction is. (P5, CoRe1)
>
> Conceptualize oxidation and reduction. (P1, LP2)

Academic rigor is another type of teacher-centered orientation for science teaching. A teacher with this orientation aims to represent a specific body of knowledge and uses instructions such as problems and activities to verify scientific concepts:

Calculate the oxidation number. (P14, CoRe1)

Differentiate electrolysis from cell processes. (P17, CoRe1)

Differentiate between spontaneous and non-spontaneous processes. (P17, CoRe2)

Process, activity-driven, and conceptual change are student-centered orientations. A teacher with process orientation aims to "help students develop the science process skills" [16] (p. 100), and students participate in activities that develop thinking processes:

Understand limitations of electronic devices. (P1, CoRe1)

Identify oxidation and reduction phenomena that occur in everyday life. (P14, CoRe1)

Understand how a battery works. (P4, CoRe2)

Students must look up differences in reactivity in a more detailed table. (P12, Vignette)

Only one segment was coded as activity-driven orientation, in which the teacher aims for students to be active:

Experimental activity performed by students, guided by a script with instructions and questions. (P4, LP2)

Three segments identify conceptual change as orientation, another type of student-centered orientation, in which the teacher aims to confront students' ideas through discussion:

Could it be that this reaction did not occur between copper and another element?. (P1, Vignette)

Make the student seek new paths. (P2, Vignette)

That he would need to be more specific, would guide him in that sense. (P16, Vignette)

These data corroborate Kind [52] and Friedrichsen et al. [18] in finding a dominance of didactic orientation. This alignment with previous research underscores the persistence of didactic teaching orientations among teachers. However, it is important to note that, while the dominant orientation remains didactic, the observed transition in teachers' orientation towards more student-centered teaching is a noteworthy development. This transition suggests that, despite the prevailing didactic approach, there is potential for change in instructional practices. This dynamic points to the complexity of the factors influencing the development of PCK and highlights the need for further exploration into the underlying drivers of these changes.

Table 3. Segments coded in relation to student-centered and teacher-centered orientations in the two distinct moments of the course.

Orientations	Teacher-Centered			Student-Centered	
	Didactic	Academic Rigor	Process	Activity-Driven	Conceptual Change
LP1	25	0	1	0	0
CoRe1	50	6	16	0	0
Vignettes	50	0	8	0	3
LP2	57	5	34	0	0
CoRe2	27	0	13	1	0

4.2. Knowledge of Science Curriculum

Knowledge of science curriculum corresponds to teachers' knowledge about programs, national documents, and relevant materials for teaching specific scientific content. Therefore, teachers' knowledge of the curriculum should include knowledge of the overall curriculum objectives, as well as the activities and materials to achieve these objectives, and knowledge of horizontal and vertical curricula for a particular subject. In relation to concepts related to redox reactions, based on the frequency of words used in the CoRe instrument, it may be inferred that the influence of the course could have had an influence on this component of teachers' pedagogical content knowledge.

It can be observed that, at the beginning of the course, some concepts were not mentioned or were mentioned infrequently. For example, the term salt bridge was not initially referenced in the course; however, at the end of the course, it was one of the most recurrent expressions in the teachers' responses (from 0 to 67). This is possible due to one of the sessions being specially planned to address and discuss concepts about the salt bridge and its functions. The frequency of the word battery also showed a noted increase (from 25 to 88).

The mention of these concepts, in addition to being associated with knowledge of the science curriculum specifically for teaching redox reactions, as they refer to the concepts necessary for teaching a specific topic, is also related to content knowledge.

Another concept that appeared to receive limited attention from the teachers initially was solutions, which was mentioned only once. However, at the end of the course, the concept of solutions was mentioned 26 times in the responses to CoRe2. The content of solutions is related to knowledge of the vertical curriculum regarding the concepts related to topics preceding redox reactions.

It was challenging to ascertain the extent of the teachers' knowledge of the vertical curriculum regarding the concepts that will follow this content. Even during the classes, when asked, the teachers did not provide extensive information about what the students would be learning next.

Regarding the curriculum resources selected by the teachers, the textbook is the most commonly used material, as affirmed by 18 out of the 20 participants. There is a noticeable tendency towards a preference for videos and texts. In general, the participants did not provide detailed explanations for their choices. From the analysis of the responses related to textbooks, it was observed that a large proportion of the participating teachers might not be familiar with the textbooks utilized in their schools. When asked about the specific volume in which concepts related to redox reactions are found, the teachers often face challenges in identifying the concepts across the various volumes. With the exception of the Citizen Chemistry collection, where the concept is concentrated in the third volume, the other textbooks present the concepts across all three volumes, mainly in the second volume [34].

When questioning the definition of the main concepts related to redox reactions (oxidation, reduction, oxidizing agent, and reducing agent), the teachers end up relying on their own knowledge instead of checking what is written in the textbook. This statement is because the teachers provided incorrect definitions, which does not align with the analysis of the textbooks (no textbook presents conceptual errors regarding these mentioned concepts). Additionally, when questioned about the didactic resources used to address the concept of redox reactions, none of the teachers emphasized the significant presence of visual representations [34,35]. Based on these facts, it can be observed that teachers are not familiar with the chemistry textbooks.

4.3. Knowledge of Students' Understanding in Science

This component is very important to highlight what teachers know about their students' knowledge and how this knowledge influences their teaching. It also demonstrates teachers' understanding of students' difficulties and conceptions. It is observed that this knowledge was not manifested during the elaboration of lesson plans and neither in the answers to the vignettes. In general, the coded segments related to difficulties and conceptions varied slightly, from 78 segments coded at the beginning to 86 segments coded at the end. However, it is noted that the frequency of difficulties considered general decreased, while difficulties considered specific increased.

Once again, merely counting the frequency will not necessarily indicate the development of this component. To assess this, the teachers' responses and manifestations were analyzed and differentiated between general and specific manifestations. Difficulties mainly appear in the CoRe instrument responses and throughout the lessons. Initially, the reported difficulties were general, with many teachers citing only prior knowledge or students do not understand difficulty in interpretation, lack of commitment to studying, difficulties in mathematical operations, or language difficulties. However, towards the end, some teachers were able to provide more details. For example, they could specify which prior knowledge poses difficulty:

> Prior knowledge of chemical bonding. (P6, CoRe2)

They can also better explain the difficulties students face in relation to language:

> Due to the terminology, students confuse oxidizing agent with reducing agent (. . .) They confuse oxidizing agent with reducing agent due to opposite charges. (P2, CoRe2)

During the discussions throughout the meetings, the difficulty in differentiating between reducing agent and oxidizing agent was also one of the most mentioned:

> For example, we tell the students, a metal was oxidized, it lost electrons, lost, I mean, when you lose, you become negative, and it became two more positive, for example, so, how did it lose and become positive? It confuses the student. It gained and lost. Gained is positive. Lost is negative . (P6, Meeting 2)

> The students cannot differentiate the anode and the cathode, if they don't have that reinforced in their minds, they will get confused. They have difficulty in writing equations and cannot identify the reducing and oxidizing agents. (P16, Meeting 5)

Based on the analysis, it can be observed that, overall, there has been an improvement in teachers' knowledge of difficulties related to the topic. Regarding conceptions, the teachers demonstrate little knowledge of alternative conceptions about the content of electrochemistry. De Jong et al. [58] state that becoming aware of students' conceptions is not an easy task, even for experienced teachers. At the beginning of the course, most of them disagree with the statement of knowing students' alternative conceptions:

> Classes change, so there are always different conceptions. (P4, questionnaire)

> I do not know the students' alternative conceptions because everyone is different, but as they arise, we adapt. (P17, questionnaire)

From the excerpts above, it can be observed that the teachers state that they do not list the conceptions because they vary from student to student. However, if they were aware of them, the teachers could mention the most well-known conceptions, those they have encountered during their classes, and even those reported in the literature. Additionally, when analyzing the teachers' justifications, particularly when they state that conceptions change because classes change, it becomes apparent that the teachers confuse alternative conceptions with prior knowledge. It can be inferred that the teachers may not demonstrate knowledge of conceptions because they are not familiar with the concept of alternative conceptions and may not even evoke them during the teaching of redox content.

It is possible that teachers do not demonstrate an understanding of certain concepts because, during their training, emphasis was not placed on considering students' alternative conceptions. They may not have received training or instruction on how to identify and address students' alternative conceptions when teaching this content. As a result, they may not be aware of the importance of recognizing and addressing these conceptions during the teaching of redox reactions. This fact is intriguing considering that 18 out of 20 teachers have a degree in chemistry education, and 10 of them have a postgraduate degree. It is also possible that teachers may have acquired in-depth knowledge of redox reaction concepts during their academic training, but the practical application of these concepts in a classroom setting may be limited. As a result, they may not incorporate specific strategies to address or assess students' understanding of these concepts during the teaching of redox reactions.

Throughout the discussions in the virtual environment and at the end of the course, particularly in the responses to the CoRe instrument, an improvement in teachers' knowledge of conceptions related to redox concepts was observed. The main conception mentioned is related to the flow of electrons:

> They think that electrons are conducted in the salt bridge. (P14, CoRe2)

> Students think that electrons swim. (P18, CoRe2)

Another conception mentioned is the indispensable presence of oxygen in redox reactions:

> Another thing, the metal was oxidized, then my student says: So, it reacted with oxygen, Oxidized means there is oxygen. They get confused there. (P10, Meeting 2)

> Students have difficulty understanding that not only those with oxygen involved undergo oxidation-reduction. (P9, Meeting 3)

4.4. Knowledge of Instructional Strategies for Teaching Science

Knowledge of instructional strategies refers to teachers' ideas about specific methods or activities to make a subject understandable for their students. It also includes how and when to use them. A total of 196 segments were coded, with 93 segments coded in the initial documents (CoRe1 and PA1) and 103 segments coded in the final documents (CoRe2 and PA2). Throughout the course, it was possible to identify evidence of strategies to be used mainly in response to the vignettes. It can be observed that strategies considered specific for teaching redox reactions increased throughout the course.

Experimentation is the most used strategy by teachers, followed by using exercises. However, teachers only mention them in general terms, without specifying the type of experimentation or the materials that would be used. The same applies to the use of exercises, where teachers mention them without providing any details about the type of exercise.

Regarding the strategies considered specific, explanations related to the content were the most frequently used by teachers, followed by the construction of a cell. The construction of a cell is considered specific knowledge because it goes beyond simply mentioning experimentation as a strategy.

Teaching strategies are related to orientations since the choices regarding strategies must align with the teaching objective. For example, a teacher with a didactic orientation will use more teacher-centered strategies:

> Gold has the highest selling price among the three metals, it's the most noble. (P1, Vignettes)

> It is important to explain that electrolysis processes consume a lot of energy and have high costs. (P14, Vignettes)

Teachers with a process orientation adopt student-centered strategies aimed at developing certain skills:

> Building cells with different materials. (P2, CoRe2)

> Assembling a Cu and Zn cell. (P7, LP2)

> Now, with the diagram ready, let's indicate the directions of the electrons, the cathode, and the anode. (P10, LP2)

A teacher also mentioned the existence of digital educational resources present in the collections of textbooks:

> Most publishers today, their differentiator, is the digital package, meaning they increasingly offer teachers in some way all these conveniences. You go in there [the digital environment], and there is a bunch of stuff. If you adopt the book, you already have access to this digital part. (P14, Meeting 3)

However, when the teachers were asked if they use simulations, they responded that they only know about them but do not use them in the classroom:

> I don't use them because I have difficulty accessing the internet at school, and many of the simulations require the internet. (P11, Meeting 3)

> In my school, there is no computer lab, which makes it difficult to use this type of strategy. (P18, Meeting 3)

Based on the teachers' statements, it can be observed that one of the issues influencing the choice in teaching strategies by teachers is the lack of equipment and internet access. The lack of laboratories for experimentation or a computer room for using simulators prevents teachers from adopting other types of strategies. Knowledge of curriculum materials and knowledge of strategies are interrelated. The material used depends on the adopted strategy. Therefore, if the teacher does not know which strategy is most suitable for the content they intend to teach, they will not know how to choose the best material.

As reported in the literature [59,60], the component of instructional strategy knowledge was the component observed to have the greatest development throughout the course. This alignment with prior research emphasizes the significance of this component in the context of professional development. However, it is essential to critically evaluate the implications of this dominance. While the substantial growth in instructional strategy knowledge is promising, it also prompts questions regarding the relative neglect of other components of PCK. This raises concerns about potential imbalances in the development of PCK and the need for a more comprehensive approach to PCK enhancement in teachers' professional development.

4.5. Knowledge of Assessment of Science Learning

This component is related to strategies for assessing students' thinking. It also includes how and when to use assessments. A total of 180 segments related to assessment were coded, with 66 related to the beginning of the course and 95 related to the end of the course. This component was not expressed throughout the responses to the vignettes.

The greatest emphasis on assessment is observed in its general aspects. In this regard, teachers only mentioned general strategies to assess understanding of the content, for example, activities, written activities, practical activities, exercises, questionnaires, experiments, reports, or assessment using ENEM (High School National Exam is a non-mandatory Brazilian national exam, which evaluates high school education in Brazil) questions. Regarding specific assessments, the most used one is the discussion of conducted experiments:

> Review of ideas about the conducted experiment. (P18, CoRe2)

> Group discussion activity on the experiment. (P9, LP2)

> Discussions and explanations about the experiment. (P17, LP2)

> Each student is asked to formulate a question about what was observed and discussed in the two classes. (P4, LP2)

The second most used type of assessment is the construction of a voltaic cell:

> Show your step-by-step process through drawings and describe the reason for the assembly. (P17, LP2)

> Reconstruction of a voltaic cell. (P5, CoRe2)

Towards the end of the course, when teachers used exercises as a form of assessment, they became more specific about the types of exercises:

> Exercise list on the concept of voltaic cells. (P8, LP2)

> Exercises specific to oxidation-reduction reactions and classification of oxidizing and reducing agents. (P11, LP2)

> In-class exercises on redox concepts, electrolytic solutions, and voltaic cells, aiming to foster content understanding. (P9, LP2)

Even when teachers were more specific, the number of coded segments related to general assessment is still high. Furthermore, no information was obtained regarding when and why teachers would use these assessments. In general, in the lesson plans developed, assessment was described as the final aspect. These results are similar to those found by Aydin and Boz [36]. The authors suggested that teachers generally lack specific domain-specific PCK for assessment in the field of electrochemical comprehension. This alignment with prior research highlights the persistent gap in teachers' understanding of assessments within their domain-specific context.

In the research field, it is evident that there is much regarding what teachers comprehend, but there is little research on what they truly understand about nuances of assessment [41]. The recognition of the importance of assessment knowledge is clear, yet it is essential to acknowledge that a deep understanding of the roles and intricacies of assessment does not spontaneously develop [61]. This raises critical questions about the existing approaches to teacher professional development and the need for more targeted strategies to bridge this gap in teachers' PCK, particularly in the realm of assessment.

4.6. Bringing Together the Components for PCK Development

The integration of PCK components is essential to becoming a successful teacher [62]. The lack of coherence between the components can be problematic as PCK should be viewed as a whole and not as separate components [36]. In other words, in the development of PCK, the components need to be interconnected to allow the entire PCK structure to function and assist student learning. As discussed earlier, a greater number of manifestations indicated individual development of the components of PCK for redox reactions. To investigate possible PCK development, segments revealing the integration of two or more components of the pentagon model were analyzed. Once a science teaching segment that indicates the presence of two or more components of PCK is identified, the teaching segment is labelled as an integration of PCK [63]. Although teachers did not consider student knowledge in lesson plan redesign, integration of other components, such as orientation and knowledge of instructional strategies, can be observed. Additionally, in the responses to the CoRe2 instrument, more integrations between the components were identified. The greatest integration observed involves orientation and instructional strategies.

In some cases (six teachers), the integration was straightforward, with one component of PCK informing another. P1, in the responses to the final CoRe (CoRe2), lists the central idea as the assembly of electrolytes and aims for students to differentiate which substance conducts electric current or not. To develop this idea, the proposed strategy is an expository lesson on electrolytic solutions, followed by a demonstrative experiment to verify the electrical conductivity of different solutions. It can be observed that the teacher's orientation suggests the adoption of the strategy. P6 also integrates these two components of PCK. In the response to CoRe2, they propose using videos about voltaic cell construction for students to understand how a cell works. Similarly, P8 demonstrates the integration between their orientation and the adopted strategy by using a demonstrative experiment for students to understand the function and concept of a salt bridge.

Some teachers (4) demonstrated integration between three components of PCK. For example, P3, in the development of the second lesson plan (LP2), states the objective for students to identify which elements oxidize, which elements reduce, what the oxidizing agent is, and what the reducing agent is in chemical equations. To achieve this objective, the teacher proposes an expository lesson using various examples of chemical equations, identifying the oxidation numbers of the elements involved and the oxidizing and reducing agents in each one. To assess students' understanding, an exercise is proposed in which students must identify which elements undergo oxidation and which undergo reduction, as well as identify the reducing and oxidizing agents. It can be observed that the teacher's orientation influenced the choice in strategy, which in turn determined the assessment.

In other cases (two teachers), integration between four components of PCK can be observed. P4 redevelops his/her lesson plan for the topic of electrolytic solutions, identifying the concepts to be covered in the lesson, with the main objective for students to identify the electrical nature of different substances. To achieve this, they plan for students to conduct an experiment in which they test the conductivity of different materials in different physical states. To assess students' understanding, a discussion about the experiment is planned to evaluate the students' ability to explain the phenomenon. In this example, it can be seen that knowledge of the curriculum suggests the adoption of a strategy, which in turn guides the assessment. Once again, the teacher's orientation shaped the choice in strategy.

Only two teachers demonstrated integration among all five components of PCK. In the responses to the CoRe2 instrument, P9 also listed the function of the salt bridge as a central idea, with the objective for students to identify the function of the salt bridge in the operation of a voltaic cell. As highlighted earlier, the concept of the salt bridge was the most emphasized throughout the course. P9 demonstrates their content knowledge by stating that the salt bridge slows down the reaction rate and increases the reaction time of the cell. Additionally, the teacher mentions that students do not know why the salt bridge is used when assembling a cell and adds that students have the misconception that electrons travel through the salt bridge. To address these issues, the teacher suggests an experimental activity in which a cell with a salt bridge and a cell without a salt bridge are set up. Through this experiment, the function of the salt bridge can be clarified, emphasizing that there are no electrons in the solution. To assess students' understanding, questions about the experiment are proposed, and students are asked to represent a cell, indicating the path of electrons and ions. In this example, the teacher's orientation, combined with knowledge of the curriculum and student understanding, influenced the choice in strategy, which in turn directed the assessment.

From the examples above, it can be observed that, despite different types of integration, the majority of teachers were able to integrate the components of PCK. However, it is evident that the level of complexity of the integrations can vary. It became clear that knowledge of instructional strategies was the PCK component most frequently connected to others. Thus, it can be inferred that this component was an influential aspect in the teachers' continuing education course. On the other hand, similar to Padilla and van Driel [64], knowledge of assessment was less frequently connected to other components of PCK. There are several possible explanations for this phenomenon: during the continuing education course, this component may not have been emphasized; knowledge of assessment is complex, involving beliefs and values about assessment [61]; and in-service teachers face difficulties in implementing assessments [54]. It is also clear that the development of one component does not necessarily mean that others will develop.

For this study, in the case of redox reactions content, the lowest connection observed was between knowledge of student understanding and knowledge of assessment. For example, the only integration between these two components was indirect, where knowledge of student conceptions informed knowledge of strategies, which in turn informed knowledge of assessment. The missing integrations may indicate that teachers need more support in these components compared to others. If teachers are supported throughout their education, it is likely that they will be able to use more components of PCK simultaneously [36].

Orientation to teaching science primarily appears in decision making, shaping teachers' choice in strategies. In this sense, the teacher's choice is filtered through their orientation. In terms of integration of PCK components, Padilla and van Driel's [64] findings also indicated that teachers' orientation was strongly related to their knowledge of instructional strategies. This correlation underscores the interconnectedness of various components of PCK. However, it also prompts us to critically examine the implications of this strong association.

While the integration of knowledge related to instructional strategies is essential, it raises questions about the relative neglect of other components of PCK. The emphasis on this particular component might inadvertently overshadow the significance of the remaining components. This implies that a more comprehensive approach to PCK development may be necessary to ensure that teachers possess a well-rounded and adaptable PCK that extends beyond just instructional strategies. Therefore, it is crucial to explore strategies that foster the harmonious integration of all PCK components, promoting a more holistic approach to teachers' professional development.

5. Conclusions

This study investigated the potential for continuing education courses to be used as a tool in the development of PCK and, consequently, in teachers' professional development.

Initially, it was expected that the continuing education course would impact the five components of teachers' PCK. The results indicate that this was indeed the case. When looking at the five dimensions of PCK, the analysis shows differences in the extent to which they were influenced during the continuing education course. It was observed that teachers made considerably more statements implying influence on their knowledge of students and their knowledge of instructional strategies than on the other three components. This was not surprising as the continuing education course was primarily based on teachers' knowledge of student conceptions and focused particularly on sharing new instructional strategies regarding the content. Additionally, from the data analysis, it was concluded that, during the continuing education course, teachers revisited their knowledge of redox reactions content, potentially leading many of them to a deeper understanding of the concepts.

While evidence of PCK development was not as pronounced, the impact of the intervention is identified in the improvement in the components of this construct. It can be observed that teachers developed the components of PCK, albeit at different levels. For example, knowledge of instructional strategies showed more development than knowledge of assessments. In addition to progress in relation to the components, integration of the components was also noted, indicating a possible improvement in PCK regarding redox reactions.

Five teachers did not show signs of integration. Seven teachers showed signs of simple integration, where one component of PCK influenced another. Four teachers demonstrated integration of three components, and two teachers demonstrated integration of four components. Two teachers demonstrated more complex integrations, where at least two components influenced and/or related to the others. The observed lack of integration may be attributed to deficiencies in initial education, such as lack of classroom experience.

It can be observed that they were able to integrate difficulties and conceptions with the choice in strategies and selection of concepts. Based on the above, it can be concluded that teachers' PCK regarding redox reactions improved and that it is possible to promote the development of this construct through specifically designed courses with this purpose and focused on specific content.

This study presents some limitations that should be considered when interpreting the results. The effect of the intervention of the professional development program may have been influenced by uncontrollable external factors, such as changes in the curriculum, educational policies, and participation in other courses. Moreover, the integration of the different components of PCK posed challenges for some participants, which can impact the extent to which PCK developed. Therefore, it is essential to interpret the results in light of these limitations and acknowledge the need for future research that addresses these issues more comprehensively.

In conclusion, the changes observed in the pedagogical content knowledge (PCK) of in-service chemistry teachers suggested a positive influence stemming from their participation in the continuing professional development program. These changes had a beneficial effect on the individual development of the components of PCK. Moreover, indications of integration between these components further hinted at the potential development of a more robust PCK, which could lead to enhanced professional growth.

Considering that, in Brazil, continuing education courses are one of the most chosen options for professional development, it is possible to promote the development of pedagogical content knowledge through courses specifically designed for this purpose, focusing on specific content. Thus, this contributes to one of the initial research objectives regarding the possibility of developing PCK for redox reactions content in a continuing education course. Additionally, future work should focus on in-service chemistry teachers' in-class practice.

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