

# LIMITATIONS OF TEACHING AND LEARNING REDOX: A SYSTEMATIC REVIEW

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## Abstract

*Redox reactions are considered one of the most difficult chemistry subjects to teach and learn. However, this is an important content that permeates several topics and includes many everyday life-related phenomena. To understand the teaching and learning difficulties of the 'redox reactions' topic, a systematic literature review was conducted. Initially, 318 articles were mapped, between the years 2000 to 2019, related to the teaching of redox reactions. The inventoried articles were analyzed to identify, in their results, the aforementioned difficulties. Only 54 presented difficulties related to teaching and learning redox reactions. To analyze these articles, the year of publication, the conceptual/procedural difficulties resulting from the study, the researched participants, and the strategies used throughout the data collection were adopted as categories. As a result, the main participants of the investigations were students. It was observed that the research studies favored bachelor degree as the level of education. Moreover, most of the analyzed studies mainly proposed experimentation as teaching strategy for teaching redox reactions. This study points to the need for continuing education courses for chemistry teachers to discuss emerging difficulties, in addition to proposing teaching strategies to remedy these difficulties.*

**Keywords:** education proposals, learning difficulties, redox reactions, state of the art

## Introduction

The term electrochemistry first appeared in 1814 with the publication of the book by George John Singer (1786-1817) entitled Elements of Electricity and Electro-Chemistry. Since then electrochemistry is a branch of science that mainly studies the interactions between chemical reactions and electrical processes. This area includes the study of redox reactions, characterized by the transfer of electrons, which are objects of study in various branches of chemistry. Besides their importance for specific areas, these reactions are involved in the operation of lamps, radios, battery-powered cell phones or batteries; in the production of gold-plated circuits; photo printing; to combat corrosion; in tests for detecting glucose in urine and alcohol in exhaled air (Mendonça et al., 2004).

The complexity of teaching and learning made redox reactions the object of study for several researchers. In this perspective, some authors developed educational proposals related to the use of multimedia and practical activities to teach this content, due to the difficulty of

students to understand the meaning of the flow of electric current, the function of the salt bridge, and the definition of cathode and anode (Karsli & Çalik, 2012; Niaz & Chacon, 2003; Sesen & Tarhan, 2013). Other studies sought to identify the main alternative conceptions evoked by students (Barke et al., 2009; Garnett & Treagust, 1992a,b; Lee, 2007; Niaz, 2002; Sanger & Greenbowe, 1997a,b; Schmidt et al., 2007).

Among the main difficulties in teaching and learning of redox reactions are electric current, salt bridge, electrical conductivity solutions, representation of redox reactions, standard reduction potential, dependence between the reduction reactions and oxidation, electron transfer process, the meaning of the oxidation number, determining the number of electrons lost or gained, identification of reagents such as reducing and oxidizing agents, identification of redox reactions, balancing redox reactions of the chemical species, identification of what suffered oxidation and reduction, differentiation of reactions in a macroscopic and microscopic level, and association of the concept of redox reactions with the context of everyday life (Barke, et al., 2009; Osterlund et al., 2010; Sanger & Greenbowe, 1997b; Soudani et al., 2000).

The inexpressive language and illustrations, sometimes inappropriate and misguided, present in textbooks may cause the difficulties related to the subject (Österlund et al., 2010; Sanger & Greenbowe, 1999). For example, textbooks usually place the anode on the left side of the stack, but they do not mention that this is a convention of the International Union of Pure and Applied Chemistry (IUPAC). Moreover, some of the learning difficulties may be due to the mixing of the levels of representation of the contents, traditionally known as macroscopic, submicroscopic and symbolic without much explanation or even prioritizing of two levels, the macroscopic and symbolic, leaving aside the submicroscopic (Johnstone, 2000).

Another aspect of the difficulty in understanding the content of redox reactions by students is based on the vocabulary and terminology used by teachers who often prioritize a quantitative explanation of this content, which is not conducive to learning concepts (Sanger & Greenbowe, 1999; H. Yarden & Yarden, 2010). Some teachers find it a difficult subject to teach, and consequently, the lesson plans hard to prepare (Ahtee et al. 2002). As they consider this topic difficult to teach, teachers leave it to the end of the school year, even knowing that there will be no time to work on the subject (Sanjuan et al., 2009).

Some studies reveal the obstacles faced by teachers to understand the definition of redox reactions, the direction of the electric current, among others (De Jong & Treagust, 2002; Özkaya, 2002; Sanger & Greenbowe, 1999). In recent surveys the Pedagogical Content Knowledge (PCK) of teachers on redox processes is analyzed (Aydin & Boz, 2013; Freire & Fernandez, 2014; Rollnick & Mavhunga, 2014).

### *Research Problem*

Over the last decades, many researchers have attempted to research and to propose teaching methodologies about redox reactions. Nevertheless, there is currently a lack of a systematic review of literature on difficulties of teaching and learning this topic. Due to the aforementioned struggles, an analysis of research published by international journals may be beneficial for science education researchers, chemistry teachers and teacher educators, which allows them to examine the research trends on the content of redox reactions. This type of review is important in order to provide a clear and comprehensive view of research on a given topic, in this case, the teaching of redox reactions. In addition, a systematic review also helps to identify research gaps and highlight important results that can be used for future research. Lastly, this specific review can help to improve knowledge about the main difficulties and conceptions regarding the content of redox reactions.

### *Research Focus*

Therefore, to provide more information on research trends in the teaching of redox reactions, it was proposed to analyze the published papers by educational journals, within a long period, from 2000 to 2019. This review focuses on the researched subjects, level of education, teaching methods and strategies, and difficulties arising from the investigations on teaching and learning the topic of redox reactions.

### *Research Aim and Research Questions*

Research aim was to identify the published research on the specific topic of difficulties in teaching redox reactions, analyzing the gaps and limitations, besides highlighting the possibilities for the future. Considering that, this research consequently addressed four research questions as follows:

1. What are the main researched subjects in empirical research that point out the difficulties about teaching and learning redox reactions?
2. What is the most researched level of education, in empirical research, which points out the difficulties in teaching and learning redox reactions?
3. What are the main research methodologies used to identify difficulties in teaching and learning redox reactions?
4. What are the difficulties in teaching and learning redox reactions resulting from empirical studies?

## **Research Methodology**

### *General Background*

Following the proposed research questions, the present study is characterized as a qualitative systematic review (Choen et al., 2018). This type of research is vital to provide an overview of knowledge about a topic, allowing the identification of relevant research for a specific issue of interest. By identifying and analyzing the conducted research and the gaps in the field, it is possible to conclude what studies need to be prioritized and what are the recommendations for further research. A descriptive content analysis (Çalik & Sözbilir, 2014) was carried out, followed by the process outlined by Newman and Gough (2020), which involves the following sequential stages: 1) develop a research question; 2) design a conceptual framework; 3) construct selection criteria; 4) develop search strategy; 5) select studies using selection criteria; 6) coding studies; 7) assess the quality of studies; and 8) synthesis results of individual studies to answer the research question.

First, the research focus was identified, i.e., difficulties arising from studies related to the teaching and learning of redox reactions and then the research questions were elaborated (see above).

### *Sample*

In the third stage of the research methodology, the following selection criteria were formulated: all articles had to report an empirical study that researched the topic of redox reactions and present difficulties related to redox reactions that were arising from the empirical studies. Studies were excluded in which (1) the focus of the investigation was not on the topic of redox reactions; (2) studies that did not present difficulties related to the content of redox reactions; (3) studies in which the difficulties were present only in the theoretical framework.

In the fourth stage, considering the criteria above, a search in the literature from 2000 to 2019 was conducted, completing a total of 20 years of research on the content of redox reactions. Searches in ERIC (Education Resources Information Center), SciELO (Scientific Electronic Library Online) and the ISI Web of Knowledge were carried out. The keywords used in the searches were: electrochemistry, redox reactions, oxidation, reduction, antioxidants and free radicals. These keywords were investigated in the fields: title, abstract, keywords, subject, and body text. Hence, 445 articles were initially found.

In the fifth stage, the selected articles were analyzed according to the selection criteria to identify the studies to be included in the review. Only 318 articles focused on the study of redox reactions. When analyzed in detail, in 101 articles the authors indicate the difficulties in teaching and learning the redox reaction, however, only 54 articles described the difficulties about redox reactions that emerged from the studies.

### *Instrument and Procedures*

These 54 selected articles were read and analyzed in detail. They were categorized into four categories (investigate subjects; level of education; methods and strategies; and difficulties arising from the investigation). In this study, the categories were based on some of those already established in the literature and used in the paper developed by groups that perform systematic review (Gallardo, 2020; Morris III, 2020; Lee et al., 2009; Teo et al., 2014; Vojíří & Rusek, 2019).

### *Data Analysis*

For data analysis, each of the selected papers was systematically analyzed into the four descriptors:

1. Investigated subjects: the analysis included the sample size and refers to what kind of subjects were researched (student, pre-service teacher, in-service teacher).
2. Level of education: refers to the level of education in which the research was conducted (elementary school, high school, bachelor degree, continuous professional developing programs, pre-service teachers).
3. Teaching methods and strategies: refers to the path taken by teachers to direct learning in their didactic proposal or in the methodology used for the development of research.
4. Difficulties arising from the search: refers to the teaching-learning difficulties involved in redox reactions.

For the first and second category, the codes were predefined, and, for the third and fourth category, the codes emerged from the analysis of the selected papers. The descriptions of the codes are in the research results section. A paper may be coded under more than one code, for example, if the study involved several levels of education or different surveyed subjects.

## **Research Results**

After selecting the articles using the proposed criteria, 54 articles presented the difficulties related to the content of redox reactions in their investigations. Table 1 shows the distribution of the studies between 2000-2019.

**Table 1**  
*Distribution of articles between 2000 to 2019*

Year	Articles (n)	Year	Articles (n)
2000	0	2010	2
2001	1	2011	4
2002	2	2012	4
2003	4	2013	3
2004	2	2014	4
2005	0	2015	3
2006	2	2016	1
2007	2	2017	4
2008	2	2018	6
2009	3	2019	5

The selected articles were distributed according to the researched subjects in four indicators: student; pre-service teacher, in-service teacher and not applicable, described in Table 2.

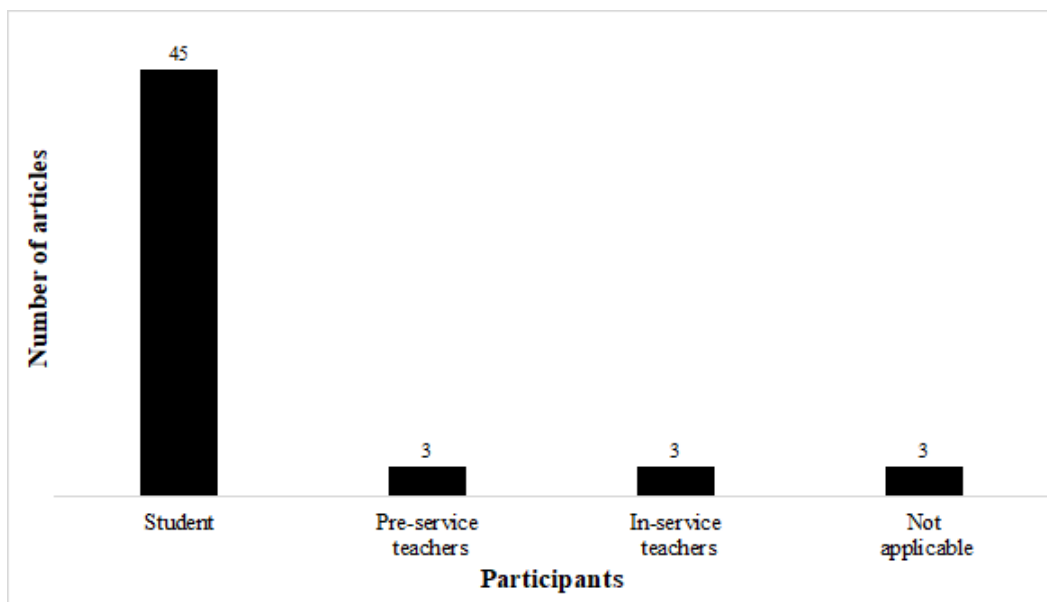
**Table 2**  
*Codes and description for researched subjects*

Codes for researched subjects	Description
Student	It includes studies with students enrolled in elementary or secondary schools.
Pre-service teachers	It includes studies with teachers in methodology courses or student teaching experiences prior to initial certification.
In-service teachers	It includes studies with certified teachers or teachers who are already teaching in a classroom. In this category no distinction was made in relation to the time of experience of teachers.
Not applicable	It includes studies that the article does not specify which subject is researched or the study is done with documents, for example, textbooks.

Figure 1 shows the number of the selected papers over the 17-year period classified in each indicator for the researched subjects - as described above.

**Figure 1**

*Distribution of the selected articles published between 2000-2019, related to the researched subjects*



According to the level of education, the 54 selected articles were distributed in six different indicators: primary education, secondary education, bachelor’s degree, teacher training, continuous professional development programs, and not applicable (Table 3).

**Table 3**

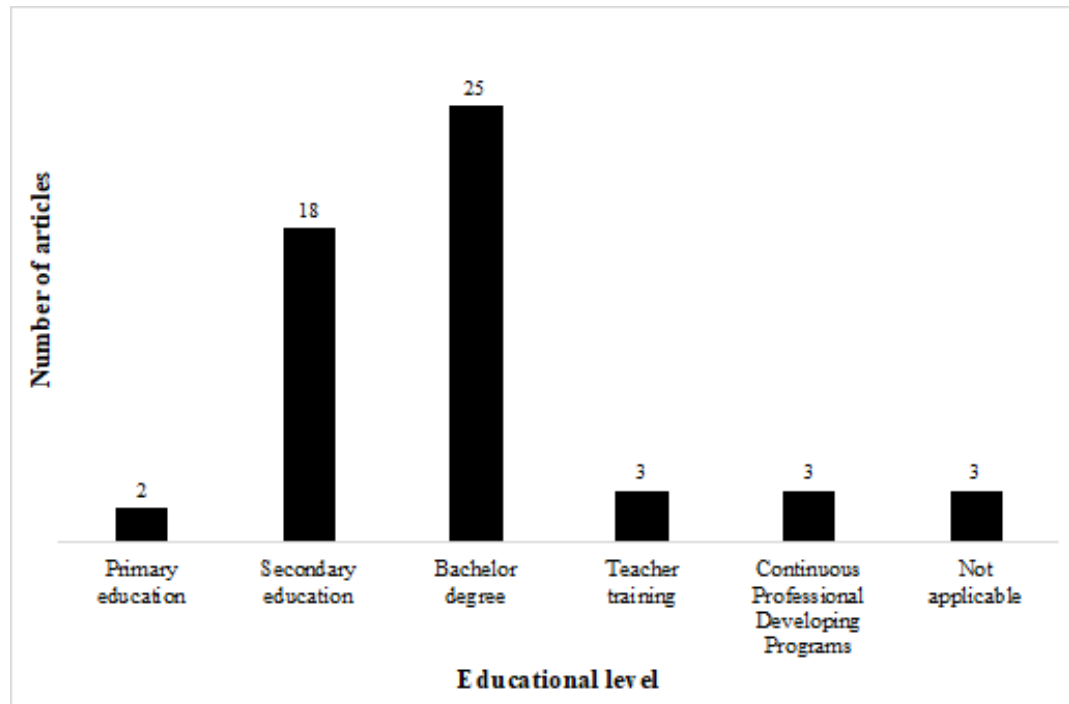
*Codes and description for level of education*

Codes for level of education	Description
Primary education	It includes studies that researched elementary school
Secondary education	It includes studies that researched secondary school or high school
Bachelor degree	It includes studies that researched an undergraduate academic degree awarded for a course, for example, Chemistry
Teacher training	It includes studies that researched an undergraduate academic degree awarded for a course design to train students to become a teacher.
Continuous Professional Developing Programs	It includes studies that researched specific activities for in-service teachers.
Not applicable	The article did not specify which level of education was researched.

Figure 2 shows the number of the selected papers over the 20-year period classified in each indicator for level of education as described above.

**Figure 2**

*Distribution of the selected articles published between 2000-2019, related to the level of education*



Regarding the methodologies and techniques, the selected articles were distributed according to the main data collection strategy adopted throughout the study. Therefore, the articles were distributed into ten descriptors that represent the main methodology used by the authors in their research on redox content (Table 4).

**Table 4**  
*Codes and description methods and strategies*

Codes for methods and strategies	Description
Experiment	Participants performed out proposed experiments, from which the research data were obtained.
Questionnaires/test	Participants provide written answers to questions prepared by researchers.
Multiple methodologies/strategies	Research that adopted more than one methodology / strategy for its development.
Interviews	Participants provide oral answers.
Textbook Analysis	Research data were obtained from a textbook analysis.
Learning sequence	Research that presented as a strategy / methodology the development of a teaching sequence.
Case study	Investigation that adopted the qualitative research, of case study type.
Problem Solving (PBL)	Research that adopted Problem Based Learning in its investigation.
Course / Minicourse / Workshop	Research that the participants participated in a course (short or long term) from which the research data were obtained.
Others	Research that does not permeate any of the descriptors presented previously.

Figure 3 shows the number of the selected papers over the 20-year period classified under each indicator for methods and strategies as described above.

**Figure 3**  
*Distribution of the selected articles published between 2000-2019, related to the methods and strategies*





The distribution of the 54 selected studies that addressed the difficulties and limitations in learning and teaching redox reactions was separated in two indicators: conceptual difficulties and procedural difficulties. Table 5 shows our final categories with the examples of the articles that address these respective difficulties in redox reactions.

**Table 5**  
*Distribution of the selected articles published between 2000-2019, related to the learning difficulties in redox reactions*

Difficulties	Articles
Understanding the electron transfer process and the movement of the electrons	Acar and Tarhan (2007); Brandriet and Bretz (2014); Cole et al. (2019); Hunter et al. (2019); Loh et al. (2018); Osman and Lee (2014); Osterlund et al. (2010); Özkaya (2002); Özkaya et al. (2006); Potgieter and Davidowitz (2011); Rahayu et al. (2011); Rosenthal and Sanger (2012); Sesen and Tarhan (2013); Silverstein (2011); Yang et al. (2004).
Understanding the meaning and assigning of oxidation numbers.	Brandriet and Bretz (2014); Childs and Sheehan (2009); Nyachwaya et al. (2011); Ozdilek (2015); Schmidt and Volke (2003); Supasorn (2015).
Differentiating the galvanic cells and electrolytic cells.	Al-Balushi et al. (2012); Osman and Lee (2014); Ozdilek, Z. (2015); Rahayu et al. (2011); Sesen and Tarhan, L. (2013); Supasorn (2015).
Understanding the function of the salt bridge.	Acar and Tarhan (2007); Al-Balushi et al. (2012); Karamustafaoğlu and Mamlok-Naaman (2015); Loh et al. (2018); Sesen and Tarhan (2013).
Understanding the potential of the half-cell and potential differences.	Acar and Tarhan (2007); Hunter et al. (2019); Messersmith (2014); Özkaya (2002); Özkaya et al. (2006).
Understanding and differentiating what is a chemical balance and an electrochemical balance.	Acar and Tarhan (2007); Cole et al. (2019); Özkaya et al. (2006); Özkaya (2002); Rosenthal and Sanger (2013).
Understanding redox reactions at the macro, micro and symbolic levels.	Haigh et al. (2012); Kelly et al. (2017); Hunter et al. (2019); Osman and Lee (2014); Valanides et al. (2003).
Understanding the functions and the charges on the anode and the cathode in galvanic cells.	Cole et al. (2019); Loh et al. (2018); Karamustafaoğlu and Mamlok-Naaman (2015); Supasorn (2015);
Understanding the presence of ions in the solution and the electrolyte conductivity	Hansen, et al. (2019); Hunter et al. (2019); Lu et al. (2019); Osman and Lee (2014).
Understanding the electrolyte concept and its electrical neutrality.	Lu et al. (2019); Rollnick and Mavhunga (2014); Tan et al. (2004).
Understanding the concentration in a redox reaction.	Acar and Tarhan (2007); Aydin et al. (2009); Gan, et al. (2018).
Differentiating ions, atoms, ionic compounds and molecules in a redox reaction.	Cole et al. (2019), Hunter et al. (2019); Kelly et al. (2017)
Understanding the Nernst equation and the relationship between Gibbs free energy, equilibrium constant and electrode potential.	Acar and Tarhan (2007); Günter and Alpat. (2017); Potgieter et al. (2008).
Understand that electron transfer changes the size of metal atoms or ions	Cole et al. (2019); Rosenthal and Sanger (2012).

Conceptual Difficulties

	Understanding the mutual dependence of oxidation and reduction reactions.	Haigh et al. (2012); Osterlund et al. (2010).
	Differentiate and understand the different models of redox reactions.	Osterlund et al. (2010); Tan et al. (2004).
	Understanding the distinction between "current/voltage" and "open circuit voltage/voltage measured with current"	Arnbjerg et al. (2019).
Procedural Difficulties	Associating the redox concepts with the observed phenomena.	Cole et al. (2019); Haigh et al. (2012); Kelly et al. (2017); Koenig et al. (2019); Llanos et al. (2019); Lee (2007); Niaz and Chacón (2003); Tarkin and Uzuntiryaki-Kondakci (2017); Testa et al. (2018); Yang et al. (2004); Yang et al. (2003).
	Identifying the species that reduces and the species that oxidizes.	Acar and Tarhan (2007); Eybe and Schmidt (2001); Messersmith (2014); Niaz (2002); Niaz and Chacón (2003); Schmidt and Volke (2003); Schultz (2008); Supasorn (2015); Rosenthal and Sanger (2012).
	Identifying reaction equations as oxidation-reduction equations	Al-Balushi et al. (2012); Hunter et al. (2019); Niaz and Chacón (2003); Noll and Hughes (2018); Own (2006); Silverstein (2011); Schultz (2008); Valanides et al. (2003); Vila and Sanz (2012).
	Predicting the products of redox reaction	Eybe and Schmidt (2001); Hamza and Wickman (2013); Hamza and Wickman (2009); Karamustafaoğlu and Mamlok-Naaman (2015); Kelly et al. (2017); Nakano et al. (2016); Ozdilek (2015); Valanides et al. (2003); Yang et al. (2004).
	Identifying the numbers of gained or lost electrons in a redox reaction; understanding stoichiometry in the electron transfer process, balancing a redox reaction	Acar and Tarhan (2007); Childs and Sheehan (2009); Cole et al. (2019); Eybe and Schmidt (2001); Geiger (2018); Kelly et al. (2017); Potgieter and Davidowitz (2011); Rosenthal and Sanger (2013).
	Identifying the anode and the cathode	Al-Balushi et al. (2012); Aydin et al. (2009); Hamza and Wickman (2013); Nakiboglu et al. (2010); Sesen and Tarhan, L. (2013); Supasorn (2015).
	Identifying reactants as oxidizing or reducing agents	Gan et al. (2018); Hunter et al. (2019); Osterlund et al. (2010); Schmidt and Volke (2003).

## Discussion

Regarding the production distribution over the years (Table 1), it can be seen that the number of publications did not vary, and the 2018 studies concentrated the largest number of publications (6 per year)- related to the difficulties in teaching and learning the topic of redox reactions. It can be inferred that the slight increase in the number of publications in these four years is a reflection of more researchers dedicating themselves to researching the aforementioned difficulties. However, these numbers are still low, considering the volume of the publications during the analyzed period.

Concerning the researched subjects (Figure 1), it was possible to identify that most papers (83%) focus their research on students, 6% on pre-service teachers and 6% on in-service teachers. Another 6% were grouped in the non-applicable category, since the research involved the analysis of a textbook (Osterlund et al., 2010), a bibliographic survey on conceptual difficulties involving redox reactions (Eybe & Schmidt, 2001) and another research discussed the concept of redox reactions (Silverstein, 2011).

The results of this research, about the surveyed participants, revealed that the studies that investigate the difficulties of in- and pre-service teachers related to the concept of redox reactions are incipient; however, in the literature, there are limitations in teaching this content

(Adu-Gyamfi et al., 2018; Ahtee et al., 2002; De Jong et al., 1995). Thus, more research related to initial and continuing training courses for teachers are needed.

The analysis of the level of education allowed us to verify what most draws the attention of researchers. It was possible to identify which levels of education are less researched and it is emphasized the need for research in these areas. In this sense, in Figure 2, there is the following trend: Bachelor's degree > Secondary education > Continuous developing programs and teacher training > Primary education. Therefore, it was highlighted that investigations about difficulties and conceptions focus their studies on students. Kindergarten was not addressed in any of the analyzed articles. This lack of research at this level of education is expected, since the content of redox reactions requires knowledge of previous chemistry concepts.

Most articles focused on bachelor's degrees (46%), for example, "The data for this study were collected in a general chemistry class for the first-semester freshmen at a mid-western university campus in the United States. The data were collected from students in the fall of 2009 and the spring of 2010, with 70 students and 40 students in the respective semesters" (Nyachwaya et al., 2011, p.124). It is inferred that research involving bachelor's degrees is the result of the understanding that there is a correlation between the students' conception and their academic performance (Alamdardoo et al., 2013).

Eighteen articles (33%) focus their research only on the secondary education, "The subjects of the study consisted of forty-one 11th grade students (17 years old) from two science classes in a high school in Izmir, which is a big city in Turkey" (Acar & Tarhan, 2007, p. 353). Research indicates that the conceptual difficulties of high school students with redox content are recurrent (Adu-Gyamfi & Ampiah, 2019), thus, it reflects in a higher number of studies with elementary school students. Adu-Gyamfi and Ampiah (2019) when investigating students' conceptions of redox reactions identified that they bring alternative conceptions and misunderstandings about this content, and they point to the need for teachers to adopt more differentiated teaching strategies. These strategies make it possible to identify alternative conceptions of their students and discuss them in the classroom.

The authors Österlund and Ekborg (2009) argue, in a research involving teaching redox models to explain electrochemistry issues that these concepts are difficult to understand. Therefore, the authors propose new strategies to teach this content in the best possible way.

According to Figure 3, multiple methodologies (33%) and experiments (20%) were the main strategy for data collection adopted throughout the studies, followed by questionnaires/tests (19%) and Others (11%). For Treagust et al. (2014) teaching strategies influence student learning. It can be inferred that the adoption of multiple methodologies adopted by most of the research, cataloged in this research, may be the result of a search by researchers to identify which one significantly influenced student learning.

One of the research studies categorized in the *Others* was performed by Silverstein (2011) who proposed a theoretical discussion on the concept of redox reactions. He concluded that "The oxidation state should, therefore, be the central pedagogic focus of discussions of redox reactions in introductory or general chemistry" (Silverstein, 2011, p. 281).

Eighteen studies performed different methodologies/strategies in their research. It can be said that the adoption of more strategies / methodologies, allows researchers to have a more global perception about what they are researching. In this regard, Yang et al. (2003) assess the impacts of an animation so that university students learn about batteries' chemical reactions. Therefore, "Students received two lectures on electrochemistry dealing with the chemical principles of how batteries generate electricity utilizing either animations or still diagrams. Students also completed a chemical knowledge test, a Flashlight pre-test and two chemistry content exams [...]" (Yang et al., 2003, p. 329).

Eleven articles used experiments (20%) to develop the content of redox reaction. In this sense, Supasorn (2015) proposed four small-scale experiments and the galvanic cell model

kit with the ability to produce various galvanic cells, to develop electrochemical content with high school students. Another research conducted an experiment and “Each student was given a written lab sheet in which the task was to construct a working galvanic cell and try to explain how and why the cell in front of him or her can produce electric current” (Hamza & Wickman, 2013, p.119).

Ten studies (19%) used questionnaires/tests as a method for investigating the contents of teaching related to redox reactions. It was deduced that the preference for using questionnaire/test is due to the possibility of accessing the conceptions of redox reactions of a greater number of participants. This descriptor presents papers in which the authors used questions (open or closed) on a given subject, specific or not. Brandriet and Bretz used “an 18-item multiple-choice assessment that measures students’ ideas about oxidation numbers, surface features of chemical reactions, electron transfer [...]” (Brandriet & Bretz, 2014, p. 730). In another example, the researchers used a specific questionnaire called Chemistry Competency Test – CCT that “consists of 65 questions of which 60 are multiple-choice (...) five questions are in an open response format” (Potgieter & Davidowitz, 2011, p. 196).

Two articles used interviews (4%) to investigate the teaching content related to redox reactions. This may indicate that research studies prefer to use questionnaires/tests to identify general patterns of a phenomenon. This methodology was described directly in the text such as Lee’s paper: “the results included interviews with 21 fifth-grade and sixth-grade students” (Lee, 2007, p. 499).

The literature points out so many problems in the teaching and learning of redox reactions, but there are few studies that discuss proposals on how to work with students’ difficulties. Many articles propose how to teach this content, most of the time using experiments, other articles show the results of pre and post test, but what is observed is the lack of a conceptual discussion about the students’ difficulty. In addition, research on proposals aimed at overcoming these difficulties is lacking.

#### *Limitations of Teaching and Learning Redox Reactions*

Despite several articles researching redox reactions, it was observed that, in the initial sample, only 54 presented difficulties related to teaching and learning redox reactions based on empirical studies. Twenty-four main areas of difficulties could be identified, and they were divided into conceptual and procedural difficulties (Table 5).

Regarding conceptual difficulties, the most documented obstacles in teaching and learning about redox reactions among the selected articles is related to understanding the electron transfer process. Acar and Tarhan (2007), Loh and Subramaniam (2018), Potgieter and Davidowitz (2011) and Rahayu et al. (2011) reported cases where students believe that electrons can flow through aqueous solutions. Brandriet and Bretz (2014) stated that, although students are able to identify where electrons are transferred to, they cannot describe the particulate process underlying the symbolic equation. In the same direction Osman and Lee (2014) contested that almost half of the students could draw the correct direction of the electrons flow, but less than 10% could give the scientific reason to explain this. Özkaya (2002) also stated that students can identify the direction of electron flow in a galvanic cell, however, they justify that electrons move from a region of high potential to a region of lower potential, a scientifically incorrect justification. Likewise, Cole et al. (2019), Özkaya et al. (2006) and Sesen and Tarhan (2013) showed that students cannot explain the flow of ions and electrons in a galvanic cell. Osterlund et al. (2010) reported that textbooks use to describe a redox reaction from the perspective of the electrons transfer; thus, they only associated reduction with the gain of electrons and oxidation with the loss of electrons.

Additionally, textbooks hardly address other models of explanation for redox reactions. Rosenthal and Sanger (2012) claimed that students do not understand that electron transfer alters the size of metal atoms or ions. Yang et al. (2004), when investigating a dry cell battery, found that students, despite understanding that electrons do not flow through the salt bridge, believe that electrons flowing through the paste.

The second most reported conceptual difficulty is the understanding of the meaning and assigning of oxidation numbers. Brandriet and Bretz (2014) indicated that students present difficulties both in calculating oxidation numbers and in differentiating them from the charges. Childs and Sheehan (2009) stated that students have difficulty in oxidation numbers because they also had difficulties in mathematics. Similarly, Nyachwaya et al. (2011) and Supasorn (2015) reported that students attributed incorrect oxidation numbers to various species and neglected oxidation numbers of charged species. Ozdilek (2015) showed that students had difficulty explaining the properties of chromium's different oxidation states. Schmidt and Volke (2003) noted that students had difficulties in attributing the oxidation number of polyatomic species.

Regarding procedural difficulties, the most documented one was related to associating the redox concepts with the observed phenomena. Tarkin and Uzuntiryaki-Kondakci (2017) reported that students had difficulty applying their theoretical knowledge about oxidation-reduction concepts when interpreting daily life events. Cole et al. (2019), Haigh et al. (2012), Kelly et al. (2017) and Testa et al. (2018) identified that students were not able to correctly correlate the color change with the oxidation / reduction of the substance. In addition, many students were unable to identify the source of the color change in solution. Lee (2007), Yang et al. (2004) and Yang et al. (2003) affirmed that students showed problems in transferring their understanding of electrochemistry concepts and principles to batteries. Llanos et al. (2019) stated that students had difficulty applying knowledge of an electrochemical method for corrosion prevention.

The second most reported procedural difficulty is related to two categories: the identifying of species that reduce and those oxidize, and to the identification of chemical equations as oxidation-reduction equations.

Acar and Tarhan (2007) reported that students thought that inert electrodes can be oxidized or reduced. Eybe and Schmidt (2001) identified that students presented misconceptions regarding the terms reduction and oxidation. Likewise, Messersmith (2014), Niaz (2002) and Niaz and Chacón (2003) stated that students were not integrated with the oxidation and reduction concepts. Schmidt and Volke (2003) showed that students confused reducing or oxidizing agents with reduction or oxidation. Schultz (2008), Supasorn (2015) and Rosenthal and Sanger (2012) stated that students had difficulties in identifying the species that reduce and those that oxidize. Supasorn (2015) said that it is because there is a difficulty in writing the correct cell reaction while Rosenthal and Sanger (2012) affirmed that it is because students were practicing incorrect ion charges.

Al-Balushi et al. (2012), Hunter et al. (2019) and Niaz and Chacón (2003) presented that the students were unable to identify whether the given situation involves a redox reaction. Silverstein (2011) reported that this difficulty is due to the many existing definitions about redox reaction. Schultz (2008) reported that students had difficulties identifying redox process. Valanides et al. (2003) showed that students had difficulties in recognizing redox reactions in the combustion process. Vila and Sanz (2012) stated that students had difficulties in identifying redox reactions in basic metabolism and photosynthesis. Noll and Hughes (2018) stated that students had trouble in analyzing redox equations.

Analyzing the difficulties presented in the researched articles, it was observed that, in most cases, more than one difficulty was reported. Brandriet e Bretz (2014) affirmed that students did not understand the concept of oxidation, nor of charges, nor the transfer of electrons. The

authors also stated that students were often unaware of their conceptual misconceptions about redox.

Another survey showed that the students had difficulties to the macroscopic level: “students appeared unable to give accounts of full observations of the redox reaction”, in addition “the use of inappropriate prior knowledge appeared to complicate their understanding at the macroscopic level (Haigh et al., 2012, p. 971). In this study, the authors argued that students had limitations in exploring experimental evidence in laboratory classes, and that this was not observed by teachers. Furthermore, they found that the observations made generally carry the influence of other topics in chemistry, less than redox reactions. Often, students still do not assimilate the submicroscopic theory, because they also have conceptual mistakes to explain the phenomena at the macroscopic level (Haigh et al., 2012).

Özkaya et al. (2006) evaluated the effectiveness of a strategy-oriented approach towards the conceptual change of students in relation to galvanic cells. The results showed that students did not understand the half-cell potential and the spontaneity of half-cell reactions. Furthermore, they did not understand the chemical balance and equilibrium electrochemical and could not explain the flow of ions and electrons in a galvanic cell.

In another study, Özkaya (2002) analyzed the difficulties of experienced teachers with the concepts of half-cell potential, cell potential, and chemical and electrochemical equilibrium in galvanic cells. The author evidenced among the conceptual limitations of the teachers that “They were not aware that the measured potential difference between a point at one electrode and a point at the other electrode or between two half-cells in a galvanic cell was due not only to the charge density at the points, but also to the potential differences between two metal–solution interfaces” (Özkaya, 2002, p. 736). The teachers also conceived that the voltmeter accurately measures the electromotive force in a galvanic cell, although in their laboratory they adopt the potentiometer to measure the electromotive force in this cell. Another difficulty was evidenced when “Although nearly all of them were able to define emf correctly, 28% could not establish the relationship between the emf of a galvanic cell and the maximum capacity of the cell to do electrical work” (Özkaya, 2002, p. 737).

In an investigation with South African students, it was found that in electrochemistry students mistakenly conceived that electrons flow through the electrolyte; thus, they did not understand stoichiometry based on electron transfer and incorrectly assigned oxidation numbers (Potgieter & Davidowitz, 2011).

Rollnick and Mavhunga (2014) developed a questionnaire to measure the pedagogical content knowledge (PCK) of experienced chemistry teachers on electrochemistry. The results show that most teachers find it difficult to accept that neutrality of half cells is maintained throughout the electrode process and “the idea of balance of charges in the two half cells of an electrochemical cell still causes problems for almost all teachers in the sample” (Rollnick & Mavhunga, 2014, p. 359).

In another investigation, which involved the implementation of a micro-scale experiment, the main limitations of the students were associated:

- (1) the number of neutral atoms increases in the anode, while it decreases in the cathode, (2) the number of metal cations increases in the reduction half-cell, while it decreases in the oxidation half-cell, (3) identified incorrect oxidation state for metal cations in each half-cell, (4) salt-generated cations transferred from the reduction to oxidation half-cell, while anions transferred from the oxidation to reduction half-cell, and (5) unaware of transfer of electrolytic anions from the reduction to oxidation half-cell (Supasorn, 2015, p. 405).

Tarhan e Acar (2007) by developing a study based on Problem Based learning highlighted that most students present “[...] some misunderstandings and misconceptions about the

concepts of oxidation, reduction, balancing oxidation-reduction reactions, cell potentials, half-cell potential and standard hydrogen electrode” (Tarhan & Acar, 2007, p. 363). Moreover, the students presented difficulties with the concepts of the effect of concentration and temperature on electrochemical equilibrium and equilibrium constant.

By adopting a test to identify the possible conceptual limitations of the students in electrochemistry, Sesen and Tarhan (2013) found that “the control group students commonly failed to explain the flow of electrons and ions, function of salt bridge, identification of anode and cathode, and confused electrolytic cell with electrochemical cells” (Sesen & Tarhan, 2013, p. 423).

Some of the difficulties pointed out in the articles presented in this review are similar to those presented more than two decades ago (Garnett & Treagust, 1992a,b; Sanger & Greenbowe, 1997a,b). Therefore, there is still a lot to be developed in terms of teaching and learning the redox concept.

### Conclusions and Implications

This study analyzed publications in educational and scientific science journals from 2000 to 2019. It is believed that this sampling allowed the mapping of published articles that address the content of redox reactions in teaching chemistry.

Regarding the educational level, most articles prioritize high school and bachelor degrees, and the elementary school was not checked by any research; thus, it is essential to have educational research proposals at this school level, especially in its final years, a period in which the study of chemistry really begins. Surveys with in-service and pre-service teachers was incipient, although studies point to the need to review electrochemistry teaching due to the difficulties to learn and teach it.

Regarding the adopted strategies or research methodologies, it was found that the analyzed articles mainly used three: multiple methodologies / strategies, experiments and questionnaire/test.

The results show that only 54 of the 318 mapped papers not only listed the limitations but they described the conceptual and procedural difficulties about redox that emerged from their research. The survey of articles on the theme of redox reactions and their respective mapping showed that this issue had been highlighted among the publication area. Another important factor was that most research is focused on high school education; however, it almost does not include courses for in-service and pre-service teachers. Thus, it can be inferred that the difficulties related to teaching this content need to address in the teacher training, overcoming the difficulties, both in teaching and learning, reported in the literature.

In general, the objectives of this research were achieved, because in the systematic review on redox reactions, it was possible to identify the study participants, the strategies/methodologies chosen by their authors and, mainly the difficulties associated with teaching and learning this content, resulting from the mapped searches. This research emphasize the importance of training courses for in-service teachers and to work with the difficulties identified in this systematic review with pre-service teachers. They can elaborate sequences and implement proposals for teaching redox reactions, to avoid these difficulties and confront alternative conceptions. In addition, activities can be carried out with teachers and future teachers who contemplate the analysis of textbooks, to correlate the difficulties identified in this research and the possible influence of this teaching material on them. Thus, it is believed that in this way it will contribute to the professional development of in-service and pre-service teachers.

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