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Green chemistry teaching: a panorama from Brazilian authors

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RESUMO

The importance of Chemistry for sustainable development has led to the development of Green Chemistry (GC) in many countries, in both academic and industrial fields. In its more than thirty years, research results have grown significantly, but the integration of this knowledge and practices in education, although encouraged, remains a challenge and deserves to be analyzed. With this scope, this research aims to characterize the contributions to the teaching of GC in Brazil, through the survey of academic productions with the participation of at least one Brazilian author. Searches were carried out in the Web of Science database, CAPES Periodicals Portal and Lattes Plataform, using different keywords involving GC and its teaching. Initial sample revealed a large community of 975 chemists interested in teaching GC in Brazil involved in 24 different types of productions, and, in the 115 articles, there are 242 distinct authors, 105 of which Brazilian. This output addresses a wide variety of topics of interest, didactic propositions and reports of teaching experiences.

PALAVRAS-CHAVE: Green chemistry education. Green chemistry. Sustainability.

INTRODUCTION

The environmental crisis, caused by anthropogenic actions, has challenged different fields of science, including chemistry and its various branches, in the development of studies on the different causes, effects, and possible solutions to environmental issues. Rockström et al. (2009) and later Steffen et al. (2015) argued for the need to identify and quantify the "planetary boundaries" that should not be exceeded to maintain environmental integrity/quality, to prevent activities that cause unacceptable environmental changes. The following ten areas were identified: climate change; ocean acidification; stratospheric ozone depletion; nitrogen cycle; phosphorus cycle; use of freshwater; land-use change; loss of biodiversity (terrestrial and marine); atmospheric aerosol loading; and chemical pollution (concerning pollution in global scale of Earth, encompassing the great variety of pollutant substances produced by industrial chemistry and dispersed in the environment along their life cycles). The study showed that for two areas (nitrogen cycle and loss of biodiversity), the boundaries have already been exceeded and that for two others (aerosols and global chemical pollution), it has not yet been possible to determine these limits (data is lacking). Diamond et al. (2015) analyzed the difficulties in defining the boundaries related to chemical pollution, emphasizing that decisions about boundaries should include societal matters, taking into account risks and uncertainties based on scientific evidence.

In this respect, Matlin et al. (2022) assert that data on the limits of the chemical pollution frontier are still deficient. However, other recent research by Persson et al. (2022) when discussing the difficulties on quantifying the frontiers related to chemical pollution, increase the scope of this concept, renamed as "new entities in the environment". Based on data on the increase of the global production of various types of substances (plastics, antibiotics, pesticides, etc.), the authors suggest that planetary boundaries have already been exceeded. Although no specific limits are presented, it is emphasized that the variety of chemical substances produced by the chemical industry makes it prohibitive to calculate their impact. In this context, Matlin et al. (2022) refer the role and contributions of Chemistry for most of the boundaries and suggest that this discussion should include other subjects, like the principles of sustainability, the use of system's thinking, and environmental impact assessments (p. 11711, Table 1).

In this sense, Matlin et al. (2022) echoes the responsibilities of Chemistry recently recognized by the UN through the establishment of a permanent panel focused on scientific policies for preventing pollution from chemical products and waste (UNEP, 2022). The responsibility of Chemistry was identified decades ago in the Brundtland Report (WCED, 1987) (in the Introduction, chapters 5 and 7) and, for example, when Chamizo (2011; 2017) acknowledged the "guilt" of Chemistry for harmful environmental practices as a driving force for the emergence of Green Chemistry (GC) or, as recently named, Green and Sustainable Chemistry (GSC). GC is an academic research field that permeates traditional areas of Chemistry (Organic, Inorganic, Analytical Chemistry, etc.), as well as a set of new industrial practices whose principles focus on pollution

prevention and risk minimization, primarily based on molecular design (ANASTAS; WARNER, 1998). One of the main justifications of GSC's major precursors was the need for commitments of GSC to Sustainable Development (SD) and, more recently, the search of solutions for chemical problems aimed at addressing sustainability challenges (MARQUES; MACHADO, 2021; MATLIN et al., 2022). However, the relations between GC and SD are not always made clear in the literature, and the limits to such intentions are often ignored, as pointed out by Marques and Machado (2014).

Over its 30 years of existence, the number of GC research publications has grown exponentially. A study by Lenoir et al. (2020), based in the Web of Science database, although with little information on how the data were obtained, points out that the number of articles involving GC went from only five in 2000 to an accumulated total of over 25,000 in 2019. These publications appeared in several journals that have become well-known and highly impactful, with the most important being, in order: Green Chemistry, from the RSC; ChemSusChem, from Wiley; ACS Sustainable Chemistry and Engineering, from ACS; and Journal of Pure and Applied Chemistry, from IUPAC. Marcelino (2020) corroborates this growth and shows the broad spectrum of research themes addressed by GC papers, involving catalysis, biomass and replacement of solvents. This vitality is also evidenced by Marques and Machado (2021) when analyzing the evolution of GC over its first 25 years.

In Brazil, GC gained momentum with the diffusion of its 12 Principles (LENARDÃO et al., 2003) and it was up to the Centro de Gestão e Estudos Estratégicos (CGEE, 2010) to highlight the pivotal role of Chemistry in addressing the environmental crisis, considering that it is virtually present at the center of all production processes and in broad sectors of the economy. CGEE emphasizes that the adoption of GC is seen as strategic for safer and cleaner industrial processes, and that its implementation in the Brazilian production matrix depends on strengthening GC education in at all levels. In this sense, CGEE created the Escola Brasileira de Química Verde (Brazilian School of Green Chemistry) to establish the concepts and applications of Green Chemistry in the dynamics of competitiveness and innovation of chemical processes in the Brazilian industry. Escola Brasileira de Química Verde is responsible for monitoring the state of the art of technologies with a view to updating curricula and developing clean processes and products that meet the country's industrial demand.

Education has been a source of concern for the main precursors of GC (COLLINS, 1995; ANASTAS; LEVY; PARENT, 2009; ANDRAOS; DICKS, 2012). However, a study on the first 25 years of GC (MARQUES; MACHADO, 2021) showed that publications directed at GC teaching (GCT) were still fewer in number than those directed at GC. This is partly understandable because it takes time to transpose, i.e., resignify and reconstruct, theoretical and practical knowledge previously produced in academic fields. However, there already research published in the last few decades about GCT proposals or experience reports developed in many countries , such as: United States of America (ANDRAOS; DICKS, 2012), China (LI; EILKS, 2021), Malaysia (KARPUDEWAN; ROTH; ISMAIL, 2015), Philippines (SANTOS; GUIDOTE, 2015), Germany (WISSINGER; KNUTSON; JAVNER, 2020), Indonesia (AULIAH; MULYADI, 2018), Nigeria

(OWOYEMI; ADESINA, 2020), Mexico (YARTO; GAVILÁN; MARTÍNEZ, 2004), Africa (LENOIR; SCHRAMN; LALAH, 2020), Latin America (ZUIN et al., 2020) and Brazil (SOUZA-AGUIAR et al., 2014).

Recently, Marques et al. (2020) presented an analysis of specific methodological aspects of GCT based on publications in the Journal of Chemical Education, highlighting that although there is an effort to integrate GC into chemistry education, proposals are often made superficially, often as an add-on or supplementary content to the existing curriculum.

Research have also established relationships/connections between chemistry education and Education for Sustainable Development (ESD) (BURMEISTER; RAUCH; EILKS, 2012; MAMINNO; ZUIN, 2015) and, more recently, Education for Sustainability (MARCELINO; SJÖSTRÖM; MARQUES, 2019; ZIDNY; SJÖSTRÖM; EILKS, 2020). Haack and Hutchinson (2016) discuss the progress of new strategies to support curricular reforms involving GC in undergraduate chemistry. Marques and Machado (2018) provide an overview of proposals for its teaching, identifying three strands and suggesting categories to examine these proposals which involved curriculum, experimental activities, didactic materials, and strategies for SD.

A significant range of studies report the occasional inclusion of GC content in the teaching of chemistry (CANN; DICKNEIDER, 2004), such as in Organic Chemistry (PILLI; ASSIS, 2018; MANSILLA; MUSCIA; UGLIAROLO, 2013), including students' interests in various topics: more efficient reactions and processes, metrics, renewable sources, catalysis, impacts and life cycle of chemical products, chemistry in the environment, recycling, and exposure and chemical hazards (GRIEGER; LEONTYEV, 2022). Experimental activities have also been pointed out as an important curricular space and formative moment to know and problematize GC (COSTA; RIBEIRO; MACHADO, 2008; GONÇALVES; MARQUES, 2016; SANDRI; SANTIN FILHO, 2017; ZUIN, 2013) addressing the experimental design (KIRCHHOFF, 2011), generation of chemical waste in teaching laboratory (PAGNO et al., 2017), implementation of GC principles (BRANDÃO, 2022), and several of its metrics (MACHADO, 2014; RIBEIRO; COSTA; MACHADO, 2010; MENDES, 2018; DOMINGUES; MAGALHÃES; SANDRI, 2022). Sandri and Santin-Filho (SANDRI; SANTIN-FILHO, 2019), based on the models of Burmeister, Rauch, and Eilks (2012) for ESD, discuss the possibilities of different didactic models for GCT, which can guide and evaluate proposals aimed at its integration into Chemistry Education from primary education up to higher education.

This brief overview shows, in addition to the growing interest in GC, the vigor of academic productions focused on its teaching. However, it also signals the need for "state of the art" studies, with refinement regarding the universe and typology of productions aimed at teaching. Equally important is to survey the growth of GC education in Brazil.

In this context, the present study sought to characterize the teaching of GC in Brazil from academic productions with the participation of Brazilian authors. This would allow, among other things, to monitor its insertion into the training of chemists and Chemistry teaching, that is, to envision the evolution of Chemistry in the pursuit of safeguarding the environment and its engagement from a sustainability perspective.

Therefore, this paper is organized into five sections. This introduction presents the importance and justifications of the topic over time. The next section exposes the presence of GC in the training of chemists and in Chemistry teaching in Brazil, and the third section presents the methodological path of our research. In the fourth section, the results are presented and discussed. Finally, conclusions are presented.

THE PRESENCE OF GREEN CHEMISTRY IN CHEMIST EDUCATION AND CHEMISTRY TEACHING IN BRAZIL

In the literature, a current and comprehensive "state of the art" on GC education in Brazil was not found. Therefore, to have a more proximal and descriptive initial overview of the immersion of GC in the teaching of chemistry, at all levels and educational modalities, we considered some previously published works that, due to different motivations, circumstances, questions, and samplings, report both the interest of researchers on this topic and bring data related to the progressive presence of GC in the teaching and formation of the chemists in our country.

The pioneers of the dissemination of GC in the national literature through scientific articles, were Sanseverino (2000; 2002), Lenardão et al. (2003), and Prado (2003). In the educational field, the first identified proposal was in 2003 (MERAT; SAN GIL, 2003), aimed at the inclusion of the concept of atom economy in the organic chemistry laboratory in undergraduate courses. Regarding teacher education and the relevance of GC for high school teaching, the first publications were found in the journals Química Nova na Escola and Química Nova, both in 2007, respectively (COELHO; MARQUES, 2007; MARQUES et al., 2007).

Dias (2016) argued that a symbolic act of formal recognition of GC by the community of chemists in Brazil was the creation of the Green Chemistry section in the 37th Annual Meeting of the Brazilian Chemical Society (RASBQ), which took place in 2014, coordinated by the Brazilian Chemical Society (SBQ). Dias (2016) analyzed all the 192 papers on GC published in this pioneering section, problematizing difficulties and obstacles faced by self-proclaimed green chemists in evolving Classical Chemistry to Green Chemistry and in overcoming what she called the "smokescreen" in the green discourses of chemists.

Roloff (2016), to understand the circulation of GC knowledge in Brazil, analyzed 50 dissertations and 27 theses in the sphere of post-graduation in Chemistry, Education, and Scientific and Technological Education, between the years 2002 and 2014, recognizing that such productions can contribute to GC teaching and influence the formation of Chemistry teachers. Roloff and Marques (2018) sought to identify the circulation of ideas about GC in 193 national scientific productions self-described as GC, published in journals and RASBQ editions between 2002 and 2014. This study found a variety of proposals with a main focus on disciplinary contents and/or the curriculum (training of the chemist and/or the teacher), most of them linking GC to Environmental Chemistry and SD.

In the context of chemistry teacher education, Leal (2002) conducted documentary research on the official programs and teaching plans of different

Chemistry Teaching Degree courses of five universities in southern Brazil, to investigate the chemical focus given to environmental problems, concluding that such courses were far from what she called Chemistry for the environment. This research was later re-analyzed later by Leal and Marques (2008), and the conclusion was that in the investigated courses the relationship of chemistry and its activities with various environmental problems was disregarded, and they identified "the almost non-existence of content that enables a view of Chemistry as an area of intervention in the environment, seeking primarily prevention" (LEAL; MARQUES, 2008).

Almeida et al. (2019) with the aim of obtaining data on the scenario of GC education in undergraduate Chemistry teaching programs, conducted a survey of Brazilian higher education institutions that offer undergraduate Chemistry Teaching Degrees. The results demonstrate that in these, GC courses are extremely scarce and that Environmental Chemistry courses, even though different from GC, are offered as optional disciplines, what might indicate it as non-essential for the education of future chemistry teachers.

Regarding the lack of studies dedicated to the integration of GC in Chemistry teachers education, Zuin and Marques (2015) described a research in which 228 works (articles, books, chapters, dissertations, and theses) were identified, between 2002 and 2013, using the keyword "green chemistry", associated to "teaching" or "education" (in Portuguese and English). This survey was carried out: i) in the five journals of SBQ, ii) in PhD theses and Master dissertations in the areas of Chemistry, Teaching/Education, and Science Education, and iii) in books and book chapters by renowned authors in the GC field. Of the total of 228 works analyzed, in all categories, only 18 (that is, less than 10% of the total) corresponded to teacher education; regarding theses and dissertations, only six dissertations and two theses were related to the subject.

Another study developed by Zuin et al. (2015) in a higher education institution in the state of São Paulo focused on Chemistry Teachers education courses in Brazil involving the environmental dimension, particularly GC. Authors evaluated 169 works obtained through searches in RASBQ and the five journals of SBQ, where they identified that about 37%, of the total productions regarding GC, bring some dialogue with other environmental terms (Environmental Education, Sustainability, Environmental Sustainability, and SD). , The authors suggest that this may represent a wake-up call to address such issues in a more critical way, especially in teacher education.

Góes et al. (2013) conducted a study with 26 teachers from a Brazilian public university, working in four different courses (Environmental Chemistry, Industrial Chemistry, Bachelor's degree and Teaching degree in Chemistry) to evaluate the Pedagogical Content Knowledge (PCK) of these teachers regarding GC, employing Grossman's Model and the models of Burmeister, Rauch, and Eilks (2012). The results showed the value of context, with teachers individually assigning more relevance to GC concepts in the Environmental Chemistry and Inorganic Chemistry courses, to the detriment of the degrees in Chemistry and Chemistry Teaching, demonstrating that teacher training was sidelined.

Pitanga, Santos, and Ferreira (2017) conducted bibliographic research in the journal Química Nova (QN) with the keywords: green chemistry, química verde,

clean technology, green synthesis, and sustainability, from 1999 to July 2015, in order to identify discourses about green chemistry and its possible appropriation as a tool for sustainability. The qualitative analysis of the 52 publications identified three categories: a) Green Synthesis, b) Clean Technologies (CT), and c) Green Chemistry as a tool for sustainability. The authors criticize the fact that most of the publications (although they do not cite numbers) are linked to the Green Synthesis category, with a predominant absence of metrics to measure the greenness of the experiments. They also criticize the discourses in the Clean Technologies category, which bring the idea of a linear growth of science and technology, where scientific development ensures technological development, which in turn ensures social development - associated with quality of life.

Roloff and Marques (2014) investigated the approach to environmental issues by interviewing chemistry teacher educators in environmental-related subjects in Chemistry teacher education programs at nine universities in the southern and southeastern regions of Brazil. Some educators stated that they worked with Environmental Education, including a Science, Technology and Society (STS) approach, and also from the perspective of GC, along with Environmental Chemistry. Regarding the category of GC as an instrument for sustainability, initially there was a close relationship with the much-criticized discourse of the Brundtland Report (WCED, 1987). In this regard, it corroborates the statement by Pitanga (2015), whose understanding is that sustainability is nothing more than an enriched concept of SD.

Brandão (2022) discussed the teaching of GC in high school and technical education, with a focus on experimentation and the STS approach, and, in one of her mappings, she included the teaching of GC in national publications up to 2017 (BRANDÃO et al., 2018), with a subsequent update until 2021 (BRANDÃO et al., 2022). Using the term "Green Chemistry" in electronic searches of keywords, abstracts, and/or the body of the text, the result pointed to 53 articles, in a universe of 260 journals, finding 1,318 references. The research indicated a noticeable growth in these two periods: an average of 2.8 publications per year until 2017 and 5.5 publications per year in the updated period. Moreira, Aires and Lorenzetti (2017) also investigated the relationship between GC and STS approach in chemistry education, arguing they contribute to minimize environmental problems and provide students with opportunities to critical thinking, making them capable of positioning themselves in the face of problems relating to the environment

In a recent study, Melo and Souza (2022) discussed the approach of GC education in Brazilian high school level, based on the selection of 18 articles published from 2011 to 2021 in renowned journals using the combination of the keywords "green chemistry" and "education". The authors highlight the scarcity of works focused on the high school level, alerting that didactic strategies and tools do not use all possibilities of GC approaches, but present only illustrative experiments for the application of GC principles and adaptation of traditional laboratory practices to match GC.

Thus, there have been several efforts by many researchers to establish an overview of GC and its education in the Brazilian context, through bibliographic research in different databases and under different inclusion criteria. However, what is perceived is that the scope of analysis ends up being limited when a

single database is searched and, consequently, a reduced number of works is identified (PITANGA; SANTOS; FERREIRA, 2017; BRANDÃO et al., 2018; MELO; SOUZA, 2022). Therefore, this work aimed to perform a comprehensive literature review for characterizing the contributions of research on GC education in Brazil, based on publications by Brazilian authors.

METHODOLOGICAL ASPECTS

The present work is characterized as qualitative research, of a descriptive and interpretative nature that, aims to characterize the teaching of Green Chemistry in Brazil from the academic productions of Brazilian authors. The searches were conducted using three databases: I) Lattes Platform; II) Web of Science (WoS); III) Portal de Periódicos CAPES (PPCAPES), from the first records found until June 2022. The queries aimed to obtain data on articles in journals, as they contain more complete information and discussions about GCT processes than other types of reports.

The choice of composing a sample of articles in journals was made because we consider that this type of production describes better the author(s)' effort in theoretical, methodological, and experiential rationalization on GC and its teaching. This option was also made because, in sequence of the present research, we intend to carry out a qualitative content analysis covering teaching methodological issues. Thus, we gathered a set of data and information about the universe and typology of the productions, their declarants, and other information related to GCT involving Brazilian authors. Such information is relevant because it seeks to provide an overview of a community of studies and research on GCT, its scope, vitality, subjects and issues of interest, challenges, formulations and teaching experiences.

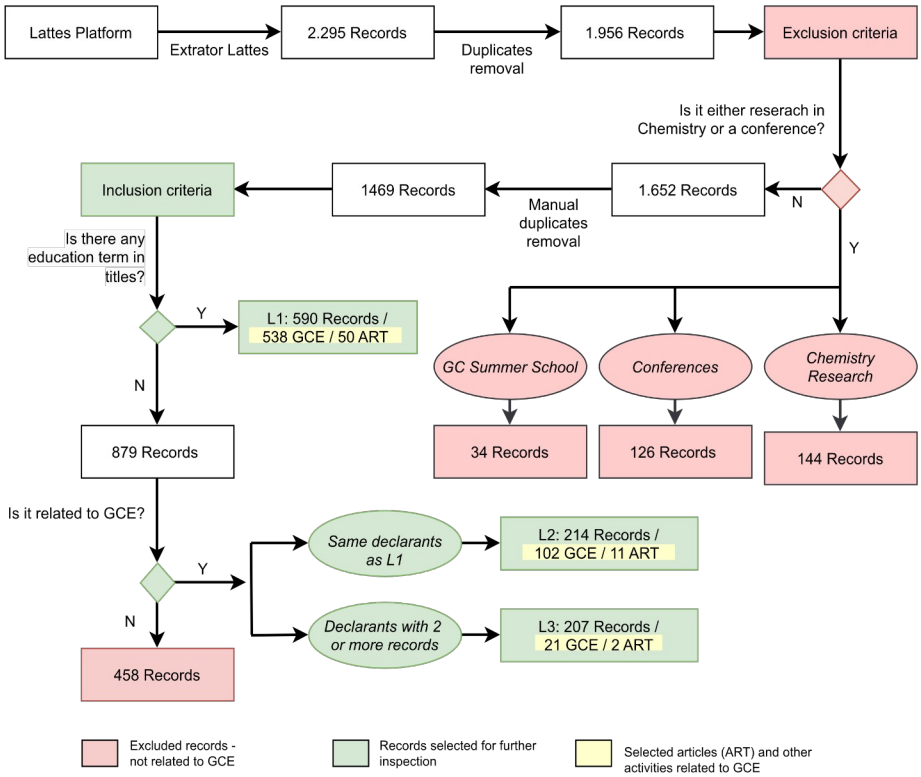
SEARCHES ON LATTES PLATAFORMA

Lattes Platform, which is a database of curricula vitae, was the first option for investigating the output on GCT in Brazil, as it brings together the academic production of most Brazilian researchers and even some foreigners. However, access to Lattes data is limited and its use requires a specific tool restricted to institutional access (Lattes Extractor, which allows research and export of information registered in curricula). After several contacts with Lattes administration and university managers, a spreadsheet with activities and publications containing the portuguese term “química verde” was obtained in May 26, 2022. Unfortunately, it was not possible to design a better query with multiple terms and filters.

Due to limitations in the access to the tool (indirect access to Lattes Extractor), complete data such as authorship, source of publication (names of conferences, journals or book series), and type of production were not provided. A total of 2,995 registers were found with the term “química verde” (hereafter called records), with information on the declarant's name (the curriculum author), activity title, and year it was either carried out or published. The absence of the source of publication in the data provided made it difficult to select

productions that deal only with GCT, and a series of complex procedures were necessary to filter out duplicates, inconsistencies and improper records. Figure 1 presents a flowchart of these procedures.

Figure 1 - Scheme of query in Lattes Platform



Source: the authors (2022).

Firstly, duplicates (referring to the same activity registered in different curricula) were removed, reducing the data to 1,956 records. Next, records were filtered by terms present in the titles, considered the following exclusion criteria: chemistry research terms (e.g., synthesis – except with educational purposes) and terms related to event names (conference, symposium, week, workshop, mini-course, lecture, video-lesson, webinar, summer school), which resulted in 1,652 records. From this set, after manual removal of duplicates, 1,469 records were obtained, which were then selected according to inclusion criteria: having a term related to the teaching of green chemistry in the title, such as teaching, learning, education, school, university, course, discipline, STS, ENEM (meaning *Exame Nacional do Ensino Médio*, i.e., National High School Exam in free translation), teacher, student, licensed, bachelor, graduation, training, graduate (the Portuguese translation of these terms were used). This process led to 589 records (this set was called L1), that were individually consulted in each declarant's Lattes curriculum to verify the type of activity and its linkage to the area of chemistry teaching.

The remaining 880 records were analyzed for their inclusion in GCT, considering two criteria: L2) records declared by researchers present in L1 (214); L3) declarants with two or more records (207). The 421 records (L2 + L3) were searched in Lattes curricula of their declarants, their title, authorship, and publication vehicle were checked, and those related to GCT were selected. Taking into account the two revisions of duplicates performed on the initial 2,295 records, 1,773 records of distinct activities were obtained, of which 661 records

(37%) are related to the teaching of GC (considering GCE registers in L1, L2 and L3: 538+102+21=661).

These manual efforts allowed to separate articles from other types of reports to be analyzed (see above introduction to this section). This sample included 63 articles, 50 obtained from L1, 11 from L2 and two from L3 (50+11+2=62).

SEARCHES IN WEB OF SCIENCE

The search of the WoS database was performed in the title, abstract, and keywords (topic search) with the following keywords and Boolean descriptors: "green chemistry" AND "educ*" OR "teach*" OR "learn*". The publication period was not limited, in order to retrieve all available items up to the search date, June 2022. After elimination of items not linked to Brazilian institutions, the search led to 88 results, of which 31 are articles on GCT, with the first one being published in 2000.

SEARCHES ON THE CAPES PERIODICALS PORTAL

For the PPCAPES searches, search was also carried out in June 2022 and the terms were associated in three different ways (Table 1) to maximize their scope. Since PPCAPES is a metasearch engine, there are difficulties in standardizing indicators across the different databases it accesses, which can affect the coherence of the extracted results. For example, when selecting a search by title, PPCAPES may search for the term exactly in the titles of one database, but expand the search to include abstracts and publication titles in another.

Table 1 - Description of searches conducted on PPCAPES and their results

Advanced Search by Subject	Search terms	Documents (n)	Documentsin Portuguese (n)	GCT Papers (n)
1	ANYWHERE:[a] “green chemistry” AND educ* OR learn* OR teach*	13.213	121	25
2	ANYWHERE: “Química verde” AND educação OR ensino OR aprendizagem	437	61	17
3	TITLE: “Química Verde”. ANYWHERE: AND educação OR ensino OR aprendizagem	482	105	9

a: "Anywhere" includes: title, abstract, keywords, and the entire text, without the option to restrict.

Source: the authors (2022).

We considered as Brazilian articles those written by authors affiliated with Brazilian institutions, published in domestic or international journals, in Portuguese or other languages. Thus, publications in Portuguese from other countries besides Brazil were disregarded. Papers retrieved in WoS and PPCAPES were then compared and duplicates removed. Next, we separated the articles that specifically addressed GCT by reading the titles, abstracts, and keywords, resulting in 51 texts in PPCAPES and 31 in WoS.

RESULTS AND DISCUSSION

The results are presented and discussed separately for the different databases from which data were extracted.

GREEN CHEMISTRY TEACHING IN BRAZIL: INCURSIONS IN THE LATTES PLATAFORM

Searches on the Lattes Platform yielded 2,995 records, the term "green chemistry" being declared by 1,470 different people. Of this total, 661 records are related to GCT in various forms, such as research reports (articles, event abstracts, books, course completion works), research projects (scientific initiation or registered in funding agencies), development of outreach activities, teaching (lectures, courses, and workshops), and research guidance. These 661 records were declared by 595 different people, of which eight are foreigners (mainly Portuguese and Colombian authors).

Table 2 - Number of records on GCT in the Lattes Platform (up to June 2022) according to the frequency of records by Brazilian declarants

Rercords per author (n)	Authors (n)
1	373
2	106
3	42
4	21
5	5
6	6
7	7
8	4
9	5
10	7
13	3
15	1
16	2
18	1
22	1
30	2
41	1

Source: the authors (2022).

Table 2 shows the frequency of activities developed by the 587 Brazilian declarants. More than half of the declarants (373) presented only one record on GCT. Only 18 declarants registered ten or more activities on GCT in their profiles, and only three presented 30 or more activities. There is a high dispersion of registers among authors: 479 (373+106) declarants have two or less registers being responsible for 585 (373+212) registers (45,7% of total); on the other hand, four declarants (1+2+1) generated 123 (22+60+41) registers (only 9,6% of total). The concentration of the number of publications by few authors is a known fact in the field of metric studies of information for mature fields (PRICE, 1971). These data suggests that GCT in Brazil is incipient, since well stablished scientific fields, with high output, have a great concentration of publications in a few authors.

However, the search in the Lattes Platform (Table 2) does not provide details on the total number of individuals involved in the activities (such as authors, co-authors, and supervisors, for example), only information on the number of declarants (profiles registered in the Lattes Platform). Therefore, the authorship of the activities in the 661 records on green chemistry education was investigated by checking and comparing each individual register in Lattes Platform about GCT, resulting in a total of 975 distinct individuals.

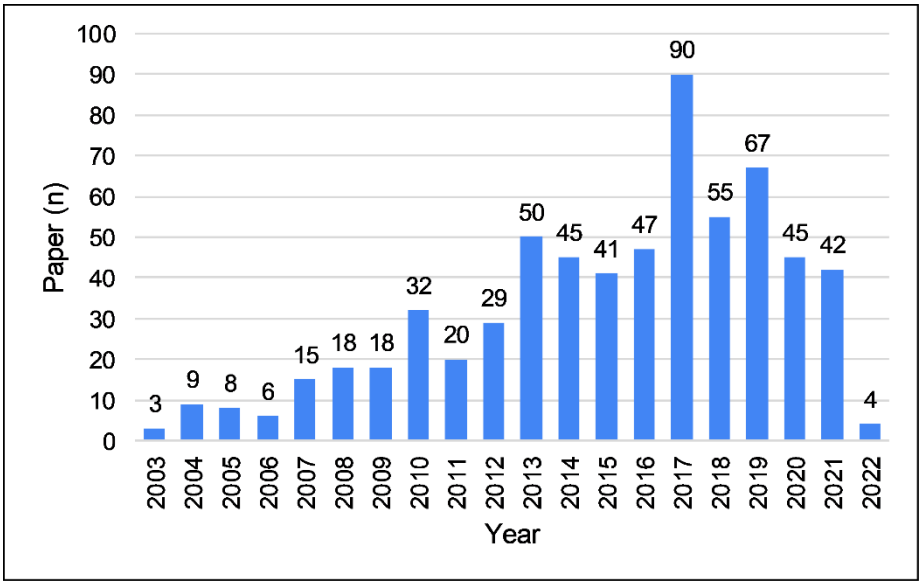
Table 3 - Typology of Productions, according to their declarants in CNPq Lattes.

Group of Activity	Activity Type	Records (n)
Presentation and Divulgation	Short course	26
	Speech	17
	Text in newspapers and non-scientific magazines	2
	Discussion panel	1
Journal article		57
Conferences	Presentation of research	156
	Research abstract	141
	Full research paper	35
	Conference organization	8
Books and chapters	Book chapter	8
	Book	3
Teaching material		11
Research guidance (final Papers, internship and others)		32
Other		37
Research and outreach	Research Project	8
	Scientific initiation	7
	Research report	1
Final papers	Undergraduate theses	77
	PhD Dissertations	10
	Master Theses	5
Total		644

Source: the authors (2022).

Table 3 presents the typologies of the 644 different records from Brazilian authors. About 50% were abstracts or presentations at events. About 15% of the productions were undergraduate thesis works, 9% were journal articles, 5% were full papers in events, and 4% were short courses on GC. Table 3 highlights the importance of events for GC dissemination and communication. The large number of undergraduate theses suggests the importance of GC in the training of chemists, especially when directed towards teacher education.

Figure 2 - Distribution of distinct records on GCT education in the Lattes Platform by year.



Source: the authors (2022).

Figure 2 shows the increasing number of works on GCT published in Brazil over the years. The first records appeared in 2003, which compares to the first record in international journals dating back to 2000 (MARQUES; MACHADO, 2018,) but the number of records grew significantly from 2007 onwards. There was a peak in production in 2017 (90 works) that may be attributed to the realization of the 46th World Chemistry Congress and IUPAC 49th General Assembly, events organized by IUPAC and SBQ in Brazil. The decrease in publications after 2019 is possibly due to the impacts of the coronavirus pandemic and budget cuts in Brazilian research funding agencies.

Due to the difficulties in accessing Lattes Extractor, only records that mentioned the term “química verde” were obtained, disregarding other relevant phrases such as green solvent, green synthesis, green experiment, and their equivalents (both in English and Portuguese). Therefore, an expansion of the research to WoS and PPCAPES databases was implemented. The joint results of the searches on the three databases are presented next.

GREEN CHEMISTRY TEACHING IN BRAZIL: INSIGHTS FROM JOURNAL ARTICLES

After checking records in the three databases and excluding duplicates, a total of 115 journal articles were obtained, of which 10 without Brazilian authors. These articles were written in Portuguese and/or their authors had profiles in the Lattes Platform, with the contribution of Portuguese authors linked to the University of Porto standing out.

Table 4 - Number of articles on GCT (up to June 2022) as a function of publication frequency by Brazilian authors

Papers by authors (n)	Authors (n)
1	195
2	32
3	9
4	1
6	1
7	2
12	1
13	1

Source: the authors (2022).

The 105 journal articles published by Brazilian authors involved 242 authors and co-authors, of which only five published five or more papers (Table 4). This accumulation of scientific production underpins the idea of the existence of a research elite in scientific fields, called Price's Elitism Law (PRICE, 1971). Alvarado (2009) defines the size of the research elite as the square root of the total number of authors, and the elite is considered productive if it publishes at least half of all papers in the area. In the present case of 242 authors of articles on GCT teaching, the calculation would suggest a research elite of 15.6. In other words, the 16 most prolific authors would constitute the research elite, responsible for publishing 53% of the articles. However, the incipiency of GCT in Brazil (see above) and the limited number of authors in the sample suggest that this statement deserves a cautionary remark.

Table 5 - Journals in which the 106 articles by Brazilian authors were published

Group	Journal Title	Papers (n)
1	Química Nova	26
1	Revista Brasileira de Ensino de Química (REBEQ)	11
2	Educación Química	5
2	Enseñanza de las Ciencias	5
2	Journal of Chemical Education	4
2	Revista Electrónica de Enseñanza de las Ciencias	4
2	ACTIO: Docência em Ciências	3
2	Amazônia – Revista de Educação em Ciências e Matemáticas	3
2	Química Nova na Escola (QNEsc)	3
2	Chemistry Education Research and Practice	2
2	Current Opinion in Green and Sustainable Chemistry	2
2	Ensaio Pesquisa em Educação em Ciências (Belo Horizonte)	2
2	Revista Brasileira de Engenharia Química	2
2	Revista Científica do IMAPES	2
2	Revista de Química Industrial	2
2	Revista Debates em Ensino de Química	2
2	Revista Vivências em Educação Química (REVEQ)	2
3	Ambiente & Sociedade	1
3	Anuário Pesquisa e Extensão	1
3	Boletim da Sociedade Portuguesa de Química	1
3	Brazilian Journal of Development	1
3	Ciência em tela	1
3	Dynamis	1
3	Eclética Química Journal	1
3	Educação Ambiental em Ação	1
3	Exatas Online	1
3	Foundations of Chemitry	1
3	Green Chemistry	1
3	Journal of Cleaner Production	1
3	Revista Acta Tecnológica	1
3	Revista Brasileira de Ciências Ambientais	1

Group	Journal Title	Papers (n)
3	Revista Brasileira de Ensino de Ciência e Tecnologia	1
3	Revista Brasileira de Pesquisa em Educação em Ciências (RBPEC)	1
3	Revista de Ensino de Bioquímica	1
3	Revista Eletrônica em Gestão, Educação e Tecnologia Ambiental	1
3	Revista Experiências em Ensino de Ciências (EENCI)	1
3	Revista Internacional de Formação de Professores	1
3	Revista Principia	1
3	Revista Virtual de Química	1
3	Science & Education (Netherlands)	1
3	Sustainability	1
3	Teoria e Prática da Educação	1
Total		105

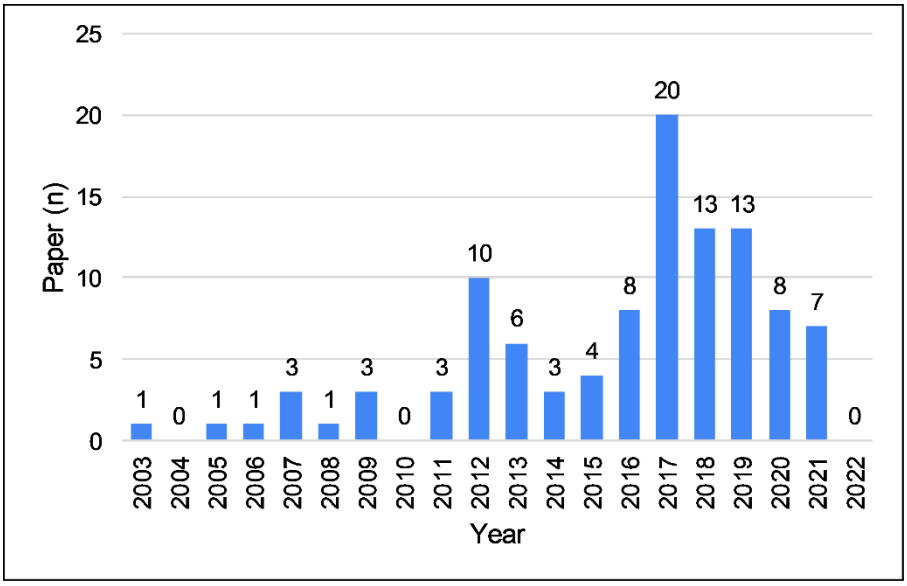
Source: the authors (2022).

Table 5 shows the 42 journals in which the 105 articles by Brazilian authors were published. Química Nova, a chemistry journal that contains a section on chemistry education, accounted for 25% of the total papers. Revista Brasileira de Ensino de Química (REBEQ), currently discontinued, contributed the second largest share, around 10%. On the other hand, Química Nova na Escola, a journal focused on chemistry teaching in primary and secondary education, presented only three articles. Nineteen journals had only one published work on GCT. This distribution shows that more than 1/3 of the articles are concentrated in two journals.

In this regard, Bradford proposed organizing the journals of a field in descending order of the number of publications, dividing the set into three parts of equal academic production (ARAÚJO, 2006). The smaller group (group 1), with the smallest number of journals, would be the specialized journals of the field, the core of the field, here represented by Química Nova and REBEQ. Group 2, of intermediate size, is formed by journals of average production and that maintain an intermediate link with the theme - in this case, journals ranging from Educación Química to REVEQ. Finally, the largest group of journals (group 3) presents only a sporadic relationship and, in this case, is formed by journals with only one paper on GCT.

Journals included in group 1 are not specific to the GCT, as evidenced by their titles, encompassing Chemistry in general (Química Nova) and Chemistry teaching (REBEQ). This demonstrates that the field of GCT still lacks its own publication venue that consolidates its own characteristics. On the other hand, the variety of the nature of the journals, expressed by their respective names, suggests that the penetration of GC, although incipient, covers a variety of diffusion spaces, related to teaching modalities, experiences or teaching proposals, among other aspects.

Figure 3 - Frequency of articles published on GCT (up to June 2022) by Brazilian authors



Source: the authors (2022).

Figure 3 shows a growing trend of articles on GCT published in journals by Brazilian authors. Starting in 2003, the number of publications reached it's a peak in 2017 (20 publications), with a slight decrease in the following years. For a possible explanation of the 2017 peak, see the comments on Figure 2.

The intention of this research is not to conduct an in-depth analysis of the content of the 106 selected articles. However, a brief explanation of the most frequent themes in the texts is presented, based on the analysis of the most used words (Table 6). The titles were all translated into English and analyzed using the web tool Text Analyzer (available at https://www.online-utility.org/text/analyzer.jsp), which counts the frequency of terms in a body of text.

Table 6 - Words that appear in at least 5% of the 116 articles on GC teaching Word

Word	Frequency in titles (n)	Frequency in titles (%)
chemistry	118	111%
green	76	72%
teaching	29	27%
experiment(s, al, ation)	22	21%
environmental	20	19%
education	16	15%
Sustain (able, ability)	14	13%
teacher(s, ')	14	13%
school	13	12%
Develop(ed, ment, ing)	11	10%
undergraduate	10	9%
didactic	10	9%
high	10	9%
organic	10	9%
Brazil(ian)	9	8%
Train(ing, ner)	9	8%
waste	9	8%
synthesis	9	8%
principle(s)	8	8%
students	8	8%

Word	Frequency in titles (n)	Frequency in titles (%)
laboratory	8	8%
analy(sis, ses, ze)	8	8%
approach	7	7%
chemical	7	7%

Source: the authors (2022).

The term "chemistry" appears in the title of all articles, sometimes more than once (thus exceeding 100%); the term "green" is present in 72% of titles. These two terms signal the need (felt by the authors) of stressing the contents of the article as green chemistry. The terms "teaching" (27%) and "didactic" (9%) may indicate the focus of the articles on teaching proposals and reports. The portion of 29% of terms related to experimentation (such as "experiment(s)", "al", "ation", and "synthesis") shows that laboratory practical activities are the main strategy for teaching GC. The terms "environmental" (19%) and "waste" (8%) indicate the relationship of GCT with environmental problems. Another recurring purpose is sustainability (13%). Teachers are listed in 13% of titles. There is also a notable focus on organic chemistry (9%) in the titles. The term "education" (15%) assumes broader characteristics than teaching, addressing issues more focused on general education. The terms "high" and "school" frequently appear together (in about 10% of titles), demonstrating a concern with discussing GC in high school education.

The list of words presented in Table 6 provides a glimpse of the focuses of GCT papers of Brazilian authors. However, this investigation requires further in-depth and qualitative study, which goes beyond the scope of this article.

CONCLUSIONS

One of the biggest challenges in this research was accessing and extracting bibliometric information from the databases, which were not always uniform or standardized. This was also the case with the main Brazilian research database, the Lattes Platform managed by the CNPq. Another issue was the specificity of WoS, which does not cover the totality of Brazilian journals, leaving out a significant set of national research. For these reasons, we compared the information from the three databases databases (WoS, Lattes Platform and PPCAPES), a cross-checking of information and data that required a lot of team effort to build the samples.

The obtained data shows the efforts of the Brazilian chemistry community (researchers of Chemistry and its teaching) to increase the presence of GC in chemistry education. There were 1,308 records of different types of productions, with 975 people involved in GC education, including students, researchers, and teachers, as authors and co-authors. However, there was little concentration of authorship, since only a few declarants had a large output and many declarants produced or participated in only one work.

Concerning the 105 articles on GCT retrieved from the three databases, it was possible to investigate the preference of Brazilian journal for publishing their results. On the other hand, the distribution of articles by the number of authors who publish the most suggests that GC Education in the country has not yet reached maturity, still being in the development phase.

Publications, and journals where they were disseminated, are mainly focused on higher education, with few articles aimed at primary and secondary education - perhaps due to difficulties in addressing GC in the scientific literacy adequate to these levels of education. In addition, there is a high concentration of publications in only two journals, which may indicate difficulties in accommodating the dissemination of works on GCT in existing journals.

The results demonstrate efforts of researchers of Chemistry and Chemistry Education in the evolution of the chemical science in the perspective of safeguarding the environment and sustainability. Our study, being more comprehensive compared to studies previously carried out by other authors, was able to add knowledge about the teaching of GC in Brazil. But it will be with the qualitative analysis of the articles that we will be able to discuss the proposals and experiences already developed, if and how such objectives are being reached, as well as to discuss the formation of a new generation of chemists. The data are encouraging because they show the interest and strength of Brazilian chemists and demonstrate the progress in the field of teaching GC in Brazil.

Ensino de química verde: um panorama a partir de autores brasileiros

RESUMO

A importância da Química para o desenvolvimento sustentável levou ao desenvolvimento da Química Verde (QV) em muitos países, tanto no campo acadêmico como industrial. Em seus mais de trinta anos, os resultados das pesquisas cresceram significativamente, mas a integração desses conhecimentos e práticas na educação, embora incentivada, continua sendo um desafio e merece ser analisada. Com esse escopo, esta pesquisa tem como objetivo caracterizar as contribuições para o ensino da QV no Brasil por meio do levantamento de produções acadêmicas com a participação de, pelo menos, um autor brasileiro. As buscas foram realizadas na base de dados Web of Science, Portal de Periódicos CAPES e Plataforma Lattes, utilizando diferentes palavras-chave envolvendo a QV e seu ensino. A amostra inicial revelou uma grande comunidade de 975 químicos interessados em ensinar QV no Brasil envolvidos em 24 tipos diferentes de produções, e, nos 115 artigos, há 242 autores distintos, sendo 105 brasileiros. Essa produção aborda uma ampla variedade de temas de interesse, proposições didáticas e relatos de experiências docentes.

PALAVRAS-CHAVE: Ensino de química verde. Química verde. Sustentabilidade.

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