Revista Brasileira de Ciência do Solo

**Division - Soil, Environment and Society** | Commission – Soils and Food Security

# Soil quality literature in Brazil: A systematic review

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**Received:** August 14, 2021
**Approved:** February 04, 2022

**How to cite:** Simon CP, Gomes TF, Pessoa TN, Soltangheisi A, Bieluczyk W, Camargo PB, Martinelli LA, Cherubin MR. Soil quality literature in Brazil: A systematic review. Rev Bras Cienc Solo. 2022;46:e0210103. https://doi.org/10.36783/18069657rbcs20210103

**Editors:** José Miguel Reichert and Jackson Adriano Albuquerque.



**ABSTRACT:** Brazilian soil scientists have increased the use of the term "soil quality" in their scientific publications in the last decade. However, it remains unclear if those publications only mention "soil quality" in a broad context, or the studies are focused on soil quality assessments, integrating soil chemical, physical and biological indicators. The objective of this systematic review was to carry out a critical analysis of the conception in using the term "soil quality" in recent publications derived from studies performed in Brazil. For this purpose, the terms [("*soil health*" or "*soil quality*" or "*qualidade do solo*") and ("*Brazil**" or "*Brasil**")] were searched in databases of *Web of Science, Scopus, and Scielo* from 2014 to 2021. Initially, 1,284 peer-reviewed papers were found, subsequently selected according to the criteria established in two filters: (*i*) First filter - studies carried out in Brazil, which mentioned at least one of the terms of interest *("soil health"* or *"soil quality"* or *"qualidade do solo"*) and that evaluated soil biological, physical or chemical indicators, assessing at least one of them; (*ii*) Second filter - studies in which all three groups of soil indicators were assessed and integrated, and presented a specific discussion about soil quality. According to the results, 36 % of the papers met the first criteria (n = 464), and only 2 % (n = 30) attended the second filter. The terms "*soil health*" or "*soil quality*" or "*qualidade do solo*" were mentioned 7 and 37 times per paper for those papers selected in the first and second filter, respectively. We evidenced in our study that the term soil quality in agricultural science papers has been predominantly used in a broad context, mostly to refer to the suitable soil conditions for plant growth. Thus, we concluded that even if the use of soil quality term is increasing in Brazilian literature, there are still very few researchers working specifically with soil quality assessments, in its full conception (*i.e.*, integrating chemical, physical and biological indicators). Therefore, there is a promising research field to be explored to promote scientific advances in the soil quality area (*e.g.*, new concepts, assessment frameworks, on-farm monitoring protocols), as well as disseminate the soil quality assessment among the Brazilian farmers, environmentalists, and other stakeholders.

**Keywords:** soil quality indicators, soil health, soil functions, soil quality assessment.

## INTRODUCTION

Soil is the foundation for multiple ecosystem functions and services that support human life on the Earth (Adhikari and Hartemink, 2016; Keesstra et al., 2016). Therefore, sustaining healthy soils is critical for increasing food production in an environmentally sustainable manner (Karlen et al., 2019). In this context, soil quality and soil health concepts have become substantially popular in the last decade, but these concepts have evolved in the literature since the early 1970s.

The use of the term "*soil quality*" nowadays is multidimensional, since various factors and renderings are historically involved in its concept (Karlen et al., 1998, 2001, 2003; Andrews et al., 2004; Rinot et al., 2019). The term "soil quality" was firstly used in the literature by Mausel (1971), who defined it as the capacity of the soil to support high grain yields with best management practices. Afterward, a soil quality movement emerged in the USA, based on the publication of the book "*Soil and water quality: An agenda for agriculture*" (National Research Council, 1993), considering that soil conservation and soil quality support the protection of water quality. After a year, Doran and Parkin (1994) expanded the concept of soil quality, emphasizing that it was not only related to plant yields, but also closely linked to the health of plants, animals, and humans. Then, two books (blue and green books) were published contextualizing the soil quality concept, "*Defining soil quality for a sustainable environment*" (Doran et al.,1994) and methodologies "*Methods for assessing soil quality*" (Doran and Jones, 1996), which became the most important references for soil quality assessment worldwide. Finally, the Soil Science Society of America (SSSA) later defined soil quality as "*the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation*" (Karlen et al., 1997), a concept which has been accepted by the science academy to this day. In Brazil, soil scientists followed these concepts, and since the beginning, soil scientists have focused on defining suitable indicators (chemical, physical and biological) and strategies to integrate them [see the comprehensive review published by Vezzani and Mielniczuk (2009)].

"*Soil quality*" and "*soil health*" terms have been broadly used in the literature as synonyms, despite the debate about these terminologies and concepts (Karlen et al., 1997; Bünemann et al., 2018; Lehmann et al., 2020; Janzen et al., 2021). In 2014, NRCS/USDA created the Soil Health Division, defining soil health as "*the continuous capacity of soil to function as a vital living ecosystem, that sustains plants, animals and humans*", a very similar concept to the last one used for soil quality (United States Department of Agriculture, 2021). Soil health term was also used in the new versions of the classic blue and green books (Doran et al., 1994; Doran and Jones, 1996) recently published by Soil Science Society of America (Karlen et al., 2021; Stott et al., 2021). Then, in systematic reviews, like this study, soil health and soil quality can be considered as synonyms.

Recent scientific studies about soil quality have emphasized that besides providing plant growth, soil supports other essential functions and ecosystem services, such as carbon sequestration, nutrient cycling, water purification, and the provision of habitats for biodiversity (Bünemann et al., 2018; Rinot et al., 2019). Therefore, soil quality needs to be correlated to the multifunctionality of the soils (Bünemann et al., 2018), combining soil chemical, physical, and biological attributes, that collectively reflect the changes induced by the use and management of soils (Rinot et al., 2019). Wherefore, soil quality assessment should include chemical, physical, and biological indicators in an integrated way analysis (Vezzani and Mielniczuk, 2009; Cherubin et al., 2016a; Bünemann et al., 2018; Rinot et al., 2019).

Given the complexity of the concepts, there is no universal methodology to evaluate soil quality. It depends on the goals and the site-specific conditions where the soil quality assessment will be conducted. Despite that, well-conducted soil quality assessments, in general, follow a three-step approach: *selection*, *interpretation* and *integration*

(Rinot et al., 2019). The *selection* of a suitable set of indicators is key to characterize and monitor the soil quality status in a given condition (Rinot et al., 2019). Four principles must be followed in this step to select suitable indicators to the minimum dataset (Doran and Parkin, 1994): *(i)* both chemical, physical and biological attributes of soils must compose the assessment; *(ii)* the indicators must be sensitive to soil changes, and represent the soil functions; *(iii)* the sampling must be accurate, with practical methodologies, easy to assess and interpret, low cost, and available for study on a time scale whenever necessary; and, *(iv)* the diagnosis, through the selected indicators, must help the decision-makers to optimize the use of environmental, human and economic resources (Andrews et al., 2004; Govaerts et al., 2006; Raiesi, 2017). More recently, those principles were also suggested in the comprehensive literature review conducted by Bünemann et al. (2018). The *interpretation* step consists of scoring each indicator by converting its measured value into 0 to 1 value. The scoring curves used to convert the measured values reflect the relationship of each indicator with one or more functions of the soil. Three scoring curve shapes are normally used to interpret the soil quality indicators: "*more is better*", "*less is better*" and "*optimal range*" (Andrews et al., 2004). At last, and fundamental to complete a soil quality assessment in its full essence, the *integration* step gathers all the information generated from the results of chemical, physical, and biological indicators and translates them into a soil quality index (SQI). The SQI is a summarized result, which must be simple, concise, and easy to interpret. There are two strategies to calculate the SQI: *i)* simple additive – all indicators have the same weight (contribution) in the index, and *ii)* weighted additive – the indicators are weighted, and then some indicators have greater influence than the others in the final index. Statistical procedures (*e.g.*, principal component analysis (PCA), partial least squares (PLS), linear correlations) and the expertise of the researcher can be highlighted as the most widespread methods to define the weight of each indicator in the integration step (Rinot et al., 2019).

The concept of the term "*soil quality*" nowadays has its principles already well placed and consolidated, as we presented above. Thus, soil quality and soil health became widely and pervasive terms in soil, plant, and environmental scientific literature (Bünemann et al., 2018; Liu et al., 2020; Janzen et al., 2021). However, it remains unclear whether the increasing number of publications mentioning the term "soil quality" are using the term in a broad context, or they are effectively focused on soil quality assessments, integrating soil chemical, physical and biological indicators to evaluate the capacity of the soil to perform its functions. In this sense, a bibliometric analysis can help map and analyze the use of "soil quality" in Brazilian literature, understand and visualize how the term has been addressed, and guide future research and public policies. Bibliometrics consists in a statistical technique, using the literature in a systematic evaluation by integrating the registered information and extracting the role and status of the information of interest (Romanelli et al., 2018).

Given the scenario, it is fundamental to understand numerically how "*soil quality*" and "*soil health*" terms have been addressed in the Brazilian literature in the last years, and then, guide the Brazilian society to the exact goal of the soil quality research, driving more effectiveness on studies related to this global concept. With this major purpose, our study aimed to carry out a critical analysis of the concept of using the term "*soil quality*" in recent publications derived from studies performed in Brazil. For this, we carefully revised and analyzed the scientific peer-reviewed papers published between 2014 and 2021 in Scopus, Web of Science, and Scielo databases, to respond to the following questions in each paper: *(i) The study assessed any indicator of soil quality or just mentioned the term? (ii) Which soil quality indicators were assessed in the study? and, (iii) Were the indicators assessed individually or in an integrated manner?* Then, gathering all this information, reading each returned paper of the databases, we constructed a systematical review, fulfilling our specific objectives, which were: *(i)* to investigate the evolution of "soil quality" recurrence in the Brazilian literature; and *(ii)* quantify how many of the filtered studies evaluated soil quality in its full essence.

## MATERIALS AND METHODS

This study was carried out systematically, constructing an investigation about the use of the term "*soil quality*" in Brazil in recent years. For this, final versions of articles published in peer-reviewed journals were revised after consulting *Scopus*, *Web of Science*, and *Scielo* databases. We chose these databases because they are widely consulted by researchers in Brazil and abroad. The terms used for searching were as follows: [("*soil health*" OR "*soil quality*" OR "*qualidade do solo*") AND ("*Brazil**" OR "*Brasil**")].

We searched the above terms within all fields of the papers, that is, the full text of all the sections was considered within the search. All publications from 2014 and 2021 were investigated, and we did not consider reviews, book chapters, and conference papers. The 2014 to 2021 period involves about two-thirds of all the published papers mentioning the term "soil quality" until October 2021 (Scopus database), representing the best ascension moment of using this term in Brazil, and most importantly, this period addresses our objective related to assessing recent conception of soil quality in the country. The search in the databases finished in June 2021.

A total of 1,284 peer-reviewed papers were found considering the three databases (Web of Science, Scopus, and Scielo). All these documents were downloaded and we read each one to apply two strategic filters, investigating the scope of these articles. For the first selection (first filter) we considered (Figure 1): *(i)* the terms of interest had to be placed in the article text and not only in the author´s affiliations, for example (outplaced); *(ii)* the study had to be carried out in Brazil; *(iii)* at least one biological, chemical or physical soil quality indicator was assessed in the study; and, (iv) the paper assessed soil parameters, and did not only evaluate plant production. After the first filtering, 464 papers were selected to be investigated in detail (Figure 1).

The Excel software was used to insert information related to the papers ($n$ = 464) and to construct a spreadsheet after the first filtration. In the end, the spreadsheet contained a large amount of inserted data, coming from these papers. For accomplishing this study, specifically, we inserted some strategic columns in the spreadsheet, distinguishing, for example, DOI, year, title, journal's name, language, authorship, which soil indicators were used and in what article section, if all the three chemical, physical and biological soil quality components were assessed, integrated, and discussed, among other information

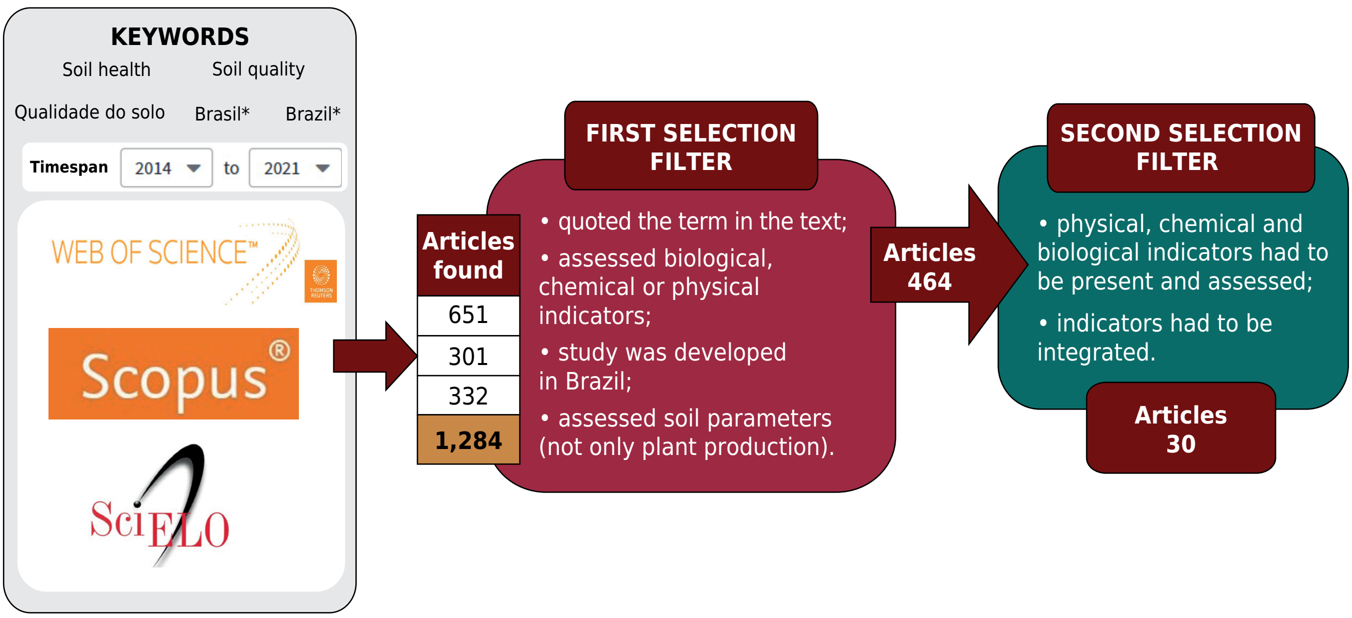


**Figure 1.** Paper search scheme: main steps and approaches used for screening and evaluating the papers.

of interest. Then, using the Excel spreadsheet database, we determined the number of occurrences of the terms “soil quality”, “soil health”, and “qualidade do solo” in each section of the paper (Title, Abstract, Keywords, Introduction, Materials and Methods, Results and Discussion and Conclusion) (Figure 2). The searching for the term in the PDF documents was done using the function *localize* (Ctrl + F).

Ultimately, for the second selection (second filter), we investigated which soil attributes (physical, chemical, biological) was used in the discussion related to soil quality. At this point, we did not select the papers that only used soil properties for the characterization of the study sites, and those that did not present indicators in the Results and/or Discussion sections. We took two steps as essential, as it follows: *(i)* we read all Discussion, or depending on the journal, the Results and Discussion section where physical, chemical, and biological soil quality indicators were discussed; and, *(ii)* both physical, chemical, and biological soil quality indicators had to be integrated by using soil health/quality index (SQI), principal component analysis (PCA), partial least squares (PLS) and / or by the use of statistic correlations, and / or expertise of the researcher (discussion about soil components in an integrated way) demonstrating the real state of the soil (Figure 2). After this second filter, only 30 papers fulfilled all the criteria (Table 1).

In our study, we discerned the groups (or components) of soil quality indicators after identifying each indicator assessed in the structure of the selected papers (Filter 1 and Filter 2). Then, we classified these soil quality indicators as (*i*) physical: soil bulk density, soil total porosity, stability of aggregates, soil resistance to penetration, and all the others; (*ii*) chemical: pH, calcium, phosphorus, potassium, magnesium, and all the others; and (*iii*) biological: soil organic matter (SOM), soil carbon stocks, microbial biomass C and N, β-glycosidase, soil macrofauna, and all the others.

For the metrics, all the papers that passed the first filter, and in sequence, the second filter, were analyzed. All this information was added to an Excel database. Then, we analyzed the evolution of the number of papers mentioning “soil quality”, frequency occurrence of the word “soil quality”, the relative frequency of the use of indicators, distribution, and intersection of chemical/ physical/biological indicators (Venn Diagram) using Excel. The graphs of *circle packing* were generated via https://rawgraphs.io/gallery/.

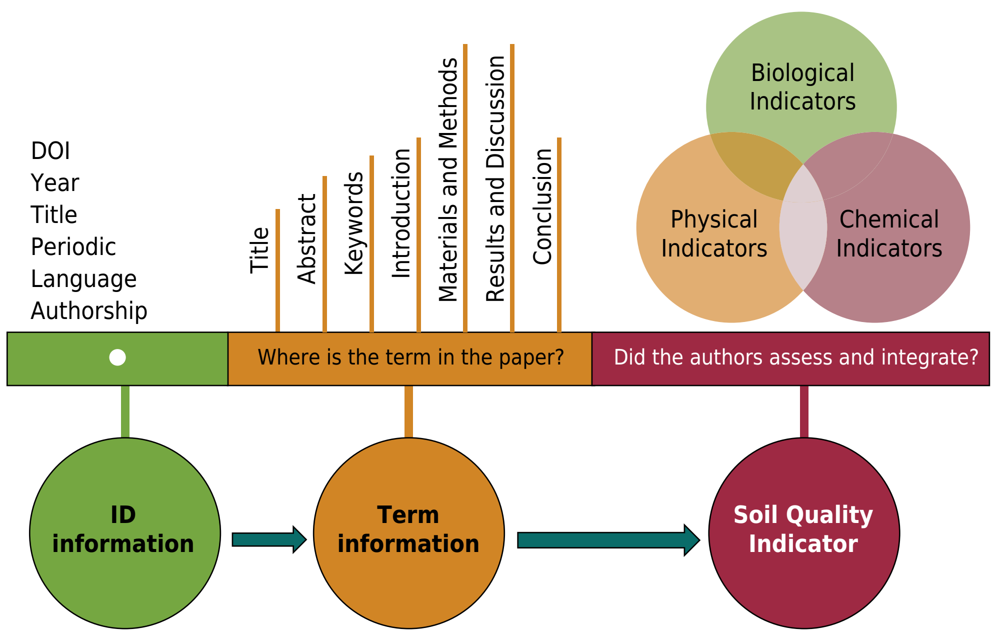


**Figure 2.** Information extracted from the papers to analyze the database.

**Table 1.** Papers that presented all the second filter criteria, that developed and distinguished soil quality assessment from 2014 to 2021

| Author | Year | Title | Periodic |
|---|---|---|---|
| Kuwano et al. | 2014 | Soil quality indicators in a Rhodic Kandiudult under different uses in northern Paraná, Brazil | Revista Brasileira de Ciência do Solo |
| Viana et al. | 2014 | Soil quality indicators for different restoration stages on Amazon rainforest | Soil and Tillage Research |
| Cherubin et al. | 2015 | Qualidade física, química e biológica de um *Latossolo* com diferentes manejos e fertilizantes | Revista Brasileira de Ciência do Solo |
| Passos et al. | 2015 | Quality indices in degraded pasture in hilly relief | Semina-Ciências Agrarias |
| Cherubin et al. | 2016 | Soil quality indexing strategies for evaluating sugarcane expansion in Brazil | Plos ONE |
| Cherubin et al. | 2016 | A Soil Management Assessment Framework (SMAF) evaluation of Brazilian sugarcane expansion on soil quality, | Soil Science Society of America Journal |
| Gonzaga et al. | 2016 | Atlantic forest soil as reference in the soil quality evaluation of coconut orchards (*Cocos nucifera L*) under different management | Semina-Ciencias Agrarias |
| Lima et al. | 2016 | Spatialization of soil quality index in the Sub-Basin of Posses, Extrema, Minas Gerais | Revista Brasileira de Engenharia Agrícola e Ambiental |
| Stefanoski et al. | 2016 | Selecting soil quality indicators for different soil management systems in the Brazilian Cerrado | Pesquisa Agropecuaria Brasileira |
| Chaves et al. | 2017 | Soil quality index of an Oxisol under different land uses in the Brazilian savannah | Geoderma regional |
| Cherubin et al. | 2017 | Soil quality evaluation using the Soil Management Assessment Framework (SMAF) in Brazilian oxisols with contrasting texture, | Revista Brasileira de Ciência do Solo |
| Satiro et al. | 2017 | Sugarcane straw removal effects on Ultisols and Oxisols in south-central Brazil, | Geoderma regional |
| Araújo et al. | 2018 | Soil quality index for cacao cropping systems | Archives of Agronomy and Soil Science |
| Barbosa et al. | 2018 | Soil attributes and quality under treated domestic sewage irrigation in sugarcane | Revista Brasileira de Engenharia Agrícola e Ambiental |
| Castioni et al. | 2018 | Soil physical quality response to sugarcane straw removal in Brazil: A multi-approach assessment | Soil and tillage research |
| Freitas et al. | 2018 | Soil quality indicator of oxisols grown with sugarcane and native forest in northeastern São Paulo state, Brazil, | Environmental earth sciences, |
| Luz et al. | 2019 | Monitoring soil quality changes in diversified agricultural cropping systems by the Soil Management Assessment Framework (SMAF) in southern Brazil | Agriculture, Ecosystems and Environment |

Continue

Continuation

| | | | |
|---|---|---|---|
| Lisboa et al. | 2019 | Applying Soil Management Assessment Framework (SMAF) on short-term sugarcane straw removal in Brazil | Industrial Crops and Products |
| Nunes et al. | 2019 | Corn root and soil health indicator response to no-till production practices | Agriculture ecosystems & environment |
| Serafim et al. | 2019 | Reference values and soil quality in areas of high soybean yield in Cerrado region, Brazil | Soil & tillage research |
| Zanatta et al. | 2019 | Carbon indices to assess quality of management systems in a Subtropical Acrisol | Scientia Agricola |
| Aragão et al. | 2020 | Microbiological indicators of soil quality are related to greater coffee yield in the Brazilian Cerrado region | Ecological Indicators |
| Farhate et al. | 2020 | Abiotic Soil Health Indicators that Respond to Sustainable Management Practices in Sugarcane Cultivation | Sustainability |
| Kazmierczak et al. | 2020 | Selection of Indicators to Discriminate Soil Tillage Systems and to Assess Soil Quality in a Red Latosol | Brazilian archives of biology and technology |
| Matos et al. | 2020 | Linkages among Soil Properties and Litter Quality in Agroforestry Systems of Southeastern Brazil | Sustainability |
| Nunes et al. | 2020 | No-till System Participatory Quality Index in land management quality assessment in Brazil | European Journal of Soil Science |
| Ruiz et al. | 2020 | Soil quality assessment of constructed Technosols: Towards the validation of a promising strategy for land reclamation, waste management and the recovery of soil functions | Journal of Environmental Management |
| Cherubin et al. | 2021 | Soil health response to sugarcane straw removal in Brazil | Industrial Crops and Products |
| Lopes et al. | 2021 | Shifts in microbial and physicochemical parameters associated with increasing soil quality in a tropical Ultisol under high seasonal variation | Soil & Tillage Research |
| Santos et al. | 2021 | Soil quality assessment using erosion-sensitive indices and fuzzy membership under different cropping systems on a Ferralsol in Brazil | Geoderma Regional |

## RESULTS AND DISCUSSION

### Evolution of the soil quality literature in Brazil

From 1,284 scientific papers retrieved from the search of the keywords in the databases, only 36 % (464) remained after the first filtering. About 2 % ($n$ = 30) were selected after using the second filter. Most of these 30 studies were carried out in the Southeast of Brazil and published in international journals (about 70 %). However, Revista Brasileira de Ciência do Solo was the Brazilian journal that presented the largest number of publications attending to the second filter criteria (Table 1). The growing interest in publishing papers in international journals or traditional Brazilian journals, currently published in English, reflects the evolution of Brazilian science in this field, not only in numbers but also in quality. Papers published in English in higher-standard peer-reviewed international and national journals have more chances to be read and cited by broader audiences, contributing to science dissemination in a more effective way.

From 2014 to 2021, the number of papers involving soil quality terms, simultaneously performed in Brazilian territory, has grown linearly, at an average rate of 65 papers per year after the first selected papers (first filter) and 4 papers per year after the second selection (second filter) (Figure 3). The growth rate for those studies which evaluated soil quality in its full essence, meaning integrating chemical, physical, and biological soil quality indicators, is still very low. These results evidence that the involvement of more researchers is still required to develop the understanding of this comprehensive topic.

Our review revealed that several papers used the term "soil quality" only in the title, or as a keyword but did not evaluate or discuss any indicators throughout the text. The investigated terms related to soil quality were mentioned 3,375 times when gathering all the papers that fulfilled the scope of the first filter (*n* = 464) and a total of 1,082 times in the 30 papers that met the scope of the second filter (Figure 4). The average number of times the term "soil quality" was cited after the first and second filters were 7 and 37, respectively. Here is important to point out that Filter 1 and Filter 2 were processed in sequence, so the 30 papers attending the second selection also composed the 464 of the first selection. Then, if we exclude these 1,082 mentions from the 3,375 times after the first filter, 434 papers (which attended only Filter 1 and were not in Filter 2) cited "soil quality" in an average of only 5 times. This basically means that if an article mentions the term "soil quality" less than 5 times in the full text, it most likely has not truly assessed soil quality.

In the second filter processing, we observed that in papers where soil quality assessment was truly developed, the methodologies and strategies were presented using the terms "soil quality" or "soil health" (*e.g.*, soil quality index, soil health index, soil quality score, soil quality indicator, soil quality assessment, and all the others). For this reason, the term

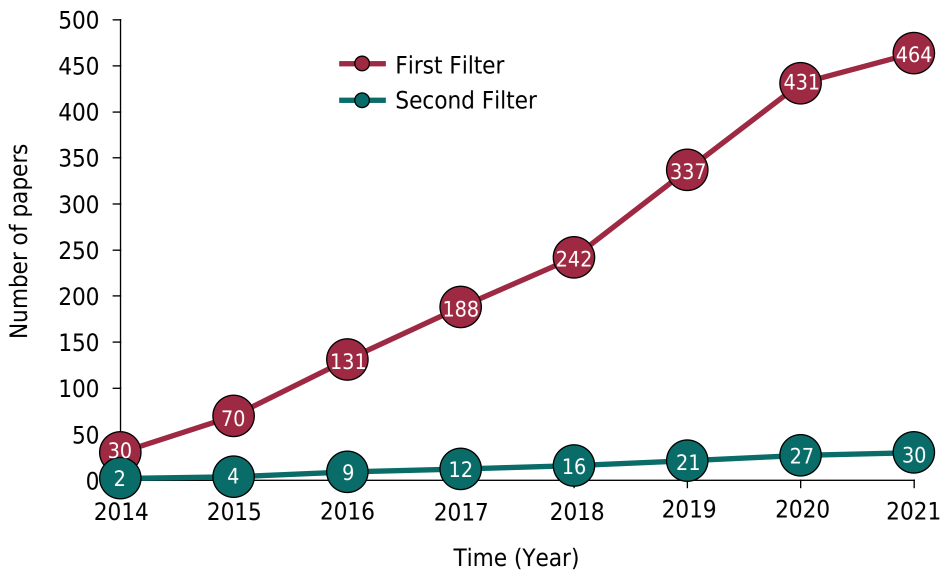


**Figure 3.** Number of publications associated with soil quality indexed in the databases from 2014 to 2021, selected in the first and second used filters. First Filter: studies carried out in Brazil, which mentioned at least one of the terms of interest (*"soil health"* or *"soil quality"* or *"qualidade do solo"*) and that evaluated soil biological, physical, or chemical indicators, accessing at least one of them. Second Filter: studies in which all three groups of soil indicators were assessed and integrated and presented a specific discussion about soil quality.

was repeated several times throughout the text in all sections of the paper (Figure 4). Soil quality was mostly cited in the *Introduction* and the *Discussion* sections after the first and the second filtering. However, after the second filter, the mention of the term "soil quality" per paper in *Introduction* and *Discussion* sections was five times higher than after the first filter. This reflects the criteria established for the second filter, in which the data had to be discussed based on the soil quality assessment. The majority of the first 464 selected papers did not evaluate the soil quality assessment, probably because these papers made only a comparative approach, confronting attribute by attribute with the literature. A soil quality assessment should account for the dynamics incorporated in the response of each variable, thus performing the integration of the groups of indicators and then discussing them.

Exploring the appearance of soil quality in different sections of the papers also helped us understand how this term was addressed. The *Abstract* of a scientific paper normally contains the most important aspects of the research. Our findings showed that the 464 studies (first filtered) cited the term "soil quality" in the *Abstract* only once per paper, while the secondly selected (*n* = 30) mentioned it four times on average. Then, we could have a preliminary guess that most of the 464 papers did not truly assess soil quality, and could have used the terms strategically to be found in research databases, as in other internet platforms. Following the paper sections, the *Introduction* of the paper is the part that shows the hypotheses, the problem, and justifies the study. Within this section, soil quality appeared 2 and 10 times per paper after the first (*n* = 464) and the second (*n* = 30) filters, respectively. We also observed that the studies developing

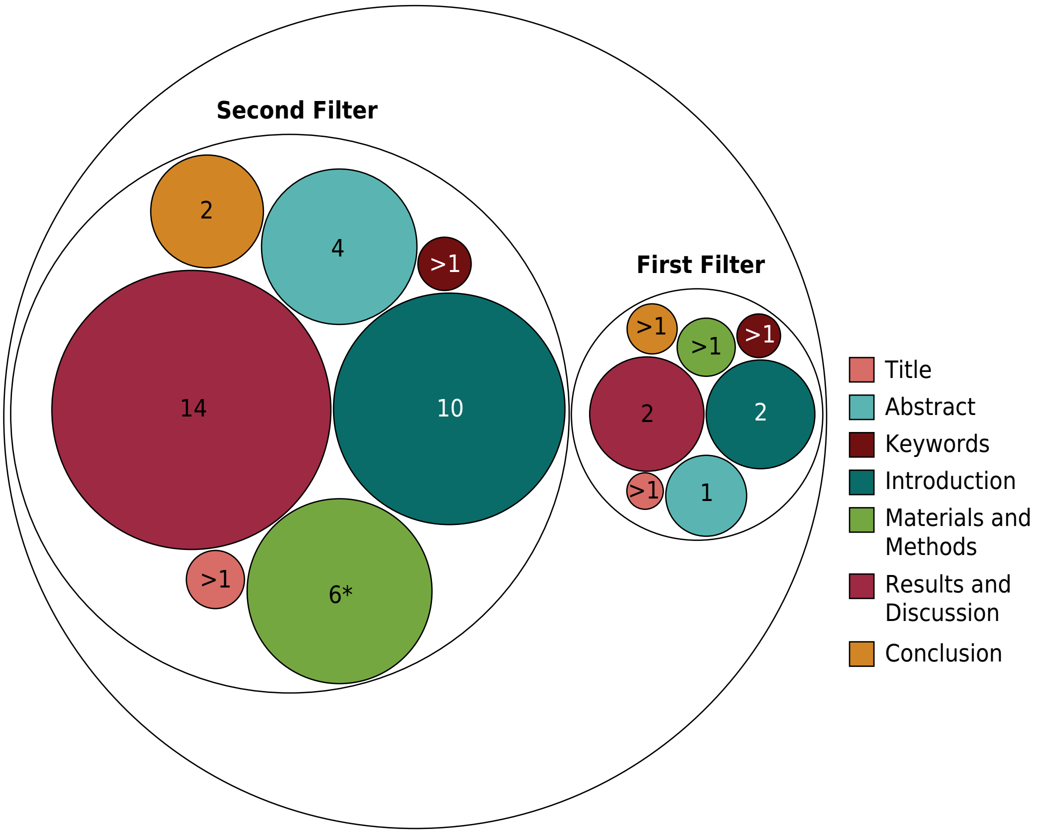


**Figure 4.** Circle packing occurrence rate using the term soil quality in the different sections of papers selected after the first filter (*n* = 464) and second (*n* = 30) filtering. The size of the circles proportionally represents the relative contribution to the total number of words found in each analyzed section. *Term occurrence rate - the average number of the of term appearance. First Filter: studies carried out in Brazil, which mentioned at least one of the terms of interest (*"soil health"* or *"soil quality"* or *"qualidade do solo"*) and that evaluated soil biological, physical, or chemical indicators, accessing at least one of them. Second Filter: studies in which all three groups of soil indicators were assessed and integrated and presented a specific discussion about soil quality.

a truly soil quality assessment normally presented the term in the hypothesis and/or objective, aiming to support the discussion. In the *Materials and Methods* section, the terms appeared once per paper (*n* = 464) after the first filter, mainly because these papers did not present soil quality methodologies, while the second filter (*n* = 30) had an average of 6 occurrences of the terms (Figure 4). Among the 30 papers, the use of soil quality indexing approaches and specific tools such as *soil quality index (SQI)* and the *Soil Management Assessment Framework* (SMAF) have been arising (*e.g.*, Cherubin et al., 2016b, 2017; Lisboa et al., 2019; Luz et al., 2019).

After the use of the first filter, 40 % of the papers cited the terms "soil quality" and "soil health" more than 5 times in their body (Figure 5), but part of them had other objectives rather than discussing soil quality directly. These objectives were: *a*) using soil quality as an adjective to characterize suitable soil conditions, but without conducting the soil quality assessment (*e.g.*, Rosa et al., 2017; Silva et al., 2017; Batistão et al., 2020); *b*) discussing the use of some tools, methodologies or strategies that can be used for soil quality evaluations (*e.g.*, Watanabe et al., 2018; Santana et al., 2021); *c*) determining the best soil indicators (*e.g.*, Stefanoski et al., 2016); *d*) elucidating the use of a certain attribute as an indicator of soil quality (*e.g.*, Rieff et al., 2016; Segat et al., 2017; Armindo and Wendroth, 2019; Prates Júnior et al., 2019); *e*) evaluating soil pollution, raising aspects inherent to heavy metals (*e.g.*, Oliveira et al., 2014; Preston et al., 2014; Silva et al., 2017; Fernandes et al., 2018; Guevara et al., 2018; Nascimento et al., 2018 and others); and *f*) use the terms to emphasize the relevance of research (*e.g.*, Pires et al., 2017; Thomaz, 2018).

When we compared the frequency of the use of the term soil quality throughout the papers, there was a substantial discrepancy; 83 % of the papers after the first filter (*n* = 464) mentioned soil quality less than 10 times, while 72 % of the papers after the second filter (*n* = 30) mentioned the term more than 21 times (Figure 5). These frequencies of occurrence of the term corroborates our selection used throughout the

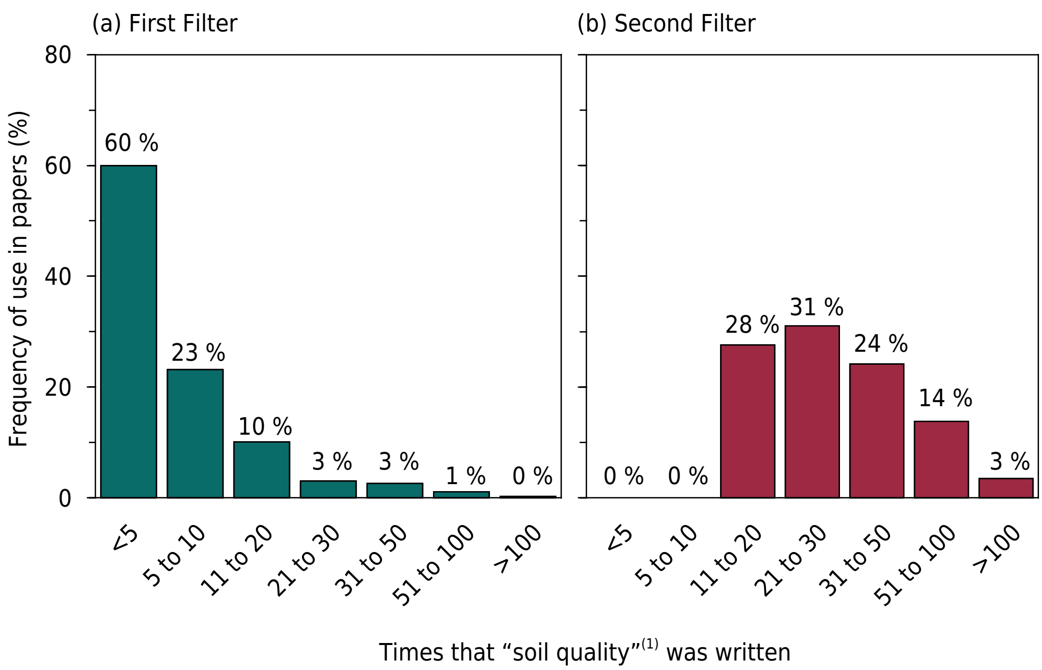


**Figure 5.** Frequency of occurrence of "soil quality" terms in the paper according to different pre-set ranges after the first (a) and second (b) systematical papers selection. [1] "*soil health*" or "*soil quality*" or "*qualidade do solo*". First Filter: studies carried out in Brazil, which mentioned at least one of the terms of interest (*"soil health"* or *"soil quality"* or *"qualidade do solo"*) and that evaluated soil biological, physical, or chemical indicators, accessing at least one of them. Second Filter: studies in which all three groups of soil indicators were assessed and integrated and presented a specific discussion about soil quality.

filters, since papers that cited “soil quality” more than 21 times were mostly directly linked to a complete soil quality assessment selected by the second filtration.

As we showed and discussed above, less than 10 % of the filtered studies evaluated soil quality in its full essence. This is very contrasting when considering that the guidelines of soil quality assessment have been developed since the 1990s, and they are well placed and consolidated in many literature references (Friedman et al., 2001; Moebius-Clune et al., 2016; Bünemann et al., 2018; Rinot et al., 2019). However, the term “soil quality” was or sometimes misused intentionally, because it is a rising term in the abroad scientific literature, or even poorly understood because its full essence has to be learned, spread and popularized in the Brazilian academy and society. The need for education about this topic is urgent given our findings. Among the best bachelor Agronomy degrees in Brazil, there is no course available exclusively focused on soil quality (Universidade de São Paulo, 2020; Universidade Federal de Viçosa, 2018; Universidade Federal de Lavras, 2019), even when the topic is mentioned within multiple other courses of the soil and vegetal production areas. Soil quality is also rarely offered as a course in Graduate Programs in Soil Science and related areas, with only a few exceptions [*e.g.*, Graduate Program of Soil Science and Plant Nutrition - Escola Superior de Agricultura “Luiz de Queiroz”, (2021); Graduate Program in Agronomy: Agriculture and Environment – Universidade Federal de Santa Maria, (2021)], showing the need for the development of this theme in Brazilian academy.

## Soil quality indicators

Soil quality evaluations combine the three areas of soil science - physics, chemistry, and biology – understanding their interactions and integrating their properties. Thus, evaluations based on one or two of these soil parameters in an isolated way are not aligned with the soil quality concept, in its full essence. The main objective of the soil quality assessment is to make the soil holistically understood as a complex and dynamic system (Andrews et al., 2004; Rinot et al., 2019), since the interpretation of agricultural production processes, the restoration of degraded areas, or the conservation of natural areas should be investigated considering different perspectives. Karlen et al. (2003) emphasized that each study in soil science is important and useful for certain applications, but also considered the need to index the dynamics of soil quality. These specific studies are important to understand specific processes and mechanisms, whether chemical, physical, or biological. Soil quality studies seek to evaluate broader aspects, relating them to functions and associated ecosystem services.

The above analogy on soil quality assessment, taking into account the related chemical, physical and biological integration, was essential to later construct our discussion about soil quality indicators. In this context, only 30 papers (second filter) of 1,284 found in literature databases (Web of Science, Scopus, and Scielo) evaluated soil quality indicators of the three groups (chemical, biological, and physical) and integrated them. Not all these 30 papers integrated all data into an overall soil quality index. Some of these studies discussed the results by indicator or component, exploring the interaction among indicators in other ways besides using SQI, as using principal component analysis (PCA), partial least squares (PLS), statistic correlations and / or the expertise of the researcher (Kuwano et al., 2014; Viana et al., 2014; Cherubin et al., 2015; Passos et al., 2015; Satiro et al., 2017; Castioni et al., 2018). In these studies, the term soil quality was validated compared to other authors who worked in similar soil and management conditions. Kuwano et al. (2014), Viana et al. (2014), Cherubin et al. (2015) and Cherubin et al. (2016a) compared the agricultural lands with reference areas, described as native vegetation adjacent to the research areas.

When considering the papers selected in the first filter ($n$ = 464), specific soil quality indicators were many times studied by authors to determine whether they are sensitive to land use change (*e.g.,* Crepaldi et al., 2014; Cherubin et al., 2016c; Oliveira Filho et al., 2016; Rieff et al., 2016 ) or even noting the degradation and restoration of natural environments (*e.g.*, Vasconcellos et al., 2016; Segat et al., 2017). Additionally, these papers have attributed validity to the study indicator without carrying out the soil quality assessment. Most of the time, they used the indicator to characterize one isolated management system and outlined broad conclusions without establishing the whole soil quality interpretation. Stenberg (1999), Karlen et al. (2003), Taylor et al. (2010), Raiesi and Kabiri (2016), Adetunji et al. (2017), and Bünemann et al. (2018) already draw attention to this practice, showing that many studies are being conducted worldwide by examining the accuracy, sensitivity, and usefulness of some soil attributes and processes at scales ranging from single points to entire land resource areas.

In 11 out of 30 papers after the second filter, SQI was mentioned in the *Results and Discussion* section (Cherubin et al., 2016ab, 2017; Gonzaga et al., 2016; Lima et al., 2016; Chaves et al., 2017; Araújo et al., 2018; Barbosa et al., 2018; Freitas et al., 2018; Luz et al., 2019; Lisboa et al., 2019). Furthermore, these authors constructed their discussion by interpreting the results obtained through the SQI, comparing their treatments and structuring a concise conclusion about the potential capacity of soil functioning based on soil functions and performance (Cherubin et al., 2016b; Luz et al., 2019). Following carefully these premises of the assessment of soil quality is indispensable to achieve reliable results and provide easy interpretation for the farmers and land managers (Karlen et al., 2008).

To infer information regarding soil quality status, many studies use reference areas (mainly native vegetation sites) to establish a paired comparison with the interest land use, such as degraded areas, stages of regeneration of degraded areas, intensive and extensive crops, changes in land use over time, use of inputs, the introduction of management practices, among others. In these cases, proper comparisons of soil properties between those are required similar inherent soil properties, climate conditions, and landscape position (Karlen et al., 2008). However, the selection of appropriate indicators and their scoring and subsequent integration should be carefully considered by researchers who have a good understanding of the concepts and applications of soil quality assessment (Andrews et al., 2004).

To represent the soil quality assessment indicators selected in the papers of the first and the second filter, the frequency of the indicators in the two sets of papers was raised (Figure 6). A total of 313 indicators of soil quality evaluation were listed, due to the use of various methods and nomenclatures, thus arising the need to group related indicators. For instance, SOM parameters correspond to the group of indicators that includes soil carbon stock, total soil organic carbon, SOM, light organic matter, particulate organic carbon, among other SOM parameters (Figure 6). Also, we omitted the indicators that did not reach the representativeness of 10 % in the occurrence frequency. On average, 10 indicators per study were selected in the second filter, this observation corroborates the findings reported by Bünemann et al. (2018), which the number of soil quality indicators included in the minimum dataset need to be reduced to make the soil quality assessment feasible to do for the users.

Soil organic matter parameters, considered as a biological indicator, had the highest frequency of occurrence, being in 66 % of the papers after the first filter (Figure 6a) and in 93 % after the second filter (Figure 6b). These parameters are considered key soil quality indicators as extremely important factors. They influence all soil's biological, chemical, and physical properties (United States Department of Agriculture, 2003) and are sensitive to management practices and land-use change. After the first filter, biological indicators were the most representative group of indicators, being evaluated in 83 % of the papers, followed by physical indicators with 55 %, and chemical indicators with 48 % (Figure 7). However, we identified that there is still a need to use specific biological indicators other than SOM. That is why, linked to SOM properties were sometimes considered chemical and sometimes biological indicators, or even both in the same paper. When we

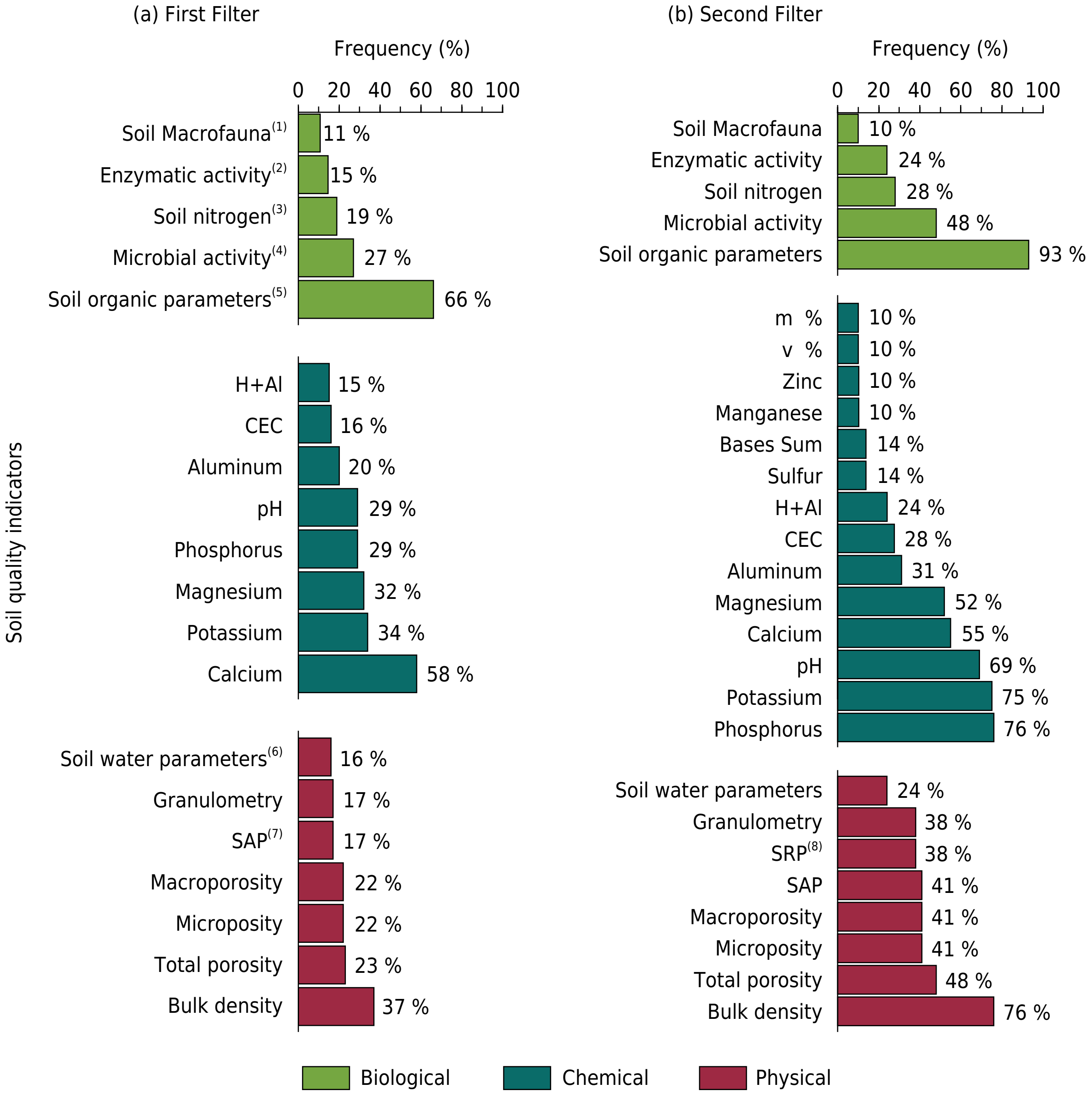


**Figure 6.** Frequency of occurrence of indicators in papers (min. 10 %) that passed through the screening of the first filter (n = 464) (a) and second filter (n = 30) (b). (1) Soil macrofauna: grouped richness, Shannon-Wiener diversity, Fisher's alpha, Margalef, Pielou equability, dominance, and all the others macrofauna related indicators. (2) Enzymatic activity: grouped urease, β-galactosidase, β-glucosidase, arilsulfatase and all the others enzymatic related parameters. (3) Soil nitrogen: grouped total N, N stock, organic nitrogen, and all the other nitrogen related assessments. (4) Microbial activity: grouped soil microbial C biomass, soil microbial N biomass, metabolic quotient ($qCO^2$), microbial quotient (qMIC) and all the other microbial indicators. (5) Soil organic parameters: grouped soil organic matter, total organic carbon, C-$CO_2$, C stock, light organic matter and all the other organic matter attributes. (6) Soil water parameters: grouped water infiltration, soil water retention, field-saturated hydraulic conductivity, available water capacity, hydraulic conductivity and all the others water related parameters. (7) SAP (soil aggregation parameters): water-stable aggregate, mean weight diameter of aggregates (MWD), geometric mean diameter of aggregates (GMD), and all the others related to soil aggregation. (8) SPR: Soil's resistance to penetration.

simulated removing indicators linked to SOM from the biological group, it became the least representative group in terms of the number appearance of evaluated indicators.

The most common indicators for the biological, physical, and chemical groups (Figure 6a) after the first filter were SOM parameters, calcium, and soil bulk density with the frequencies of 66, 58, and 37 %, respectively. The second filter obtained SOM parameters (93 % frequency), the chemical was phosphorus (P) (76 %), and the physical was soil bulk density (76 %), obeying one of the premises of the evaluation of the soil quality. This premise is to

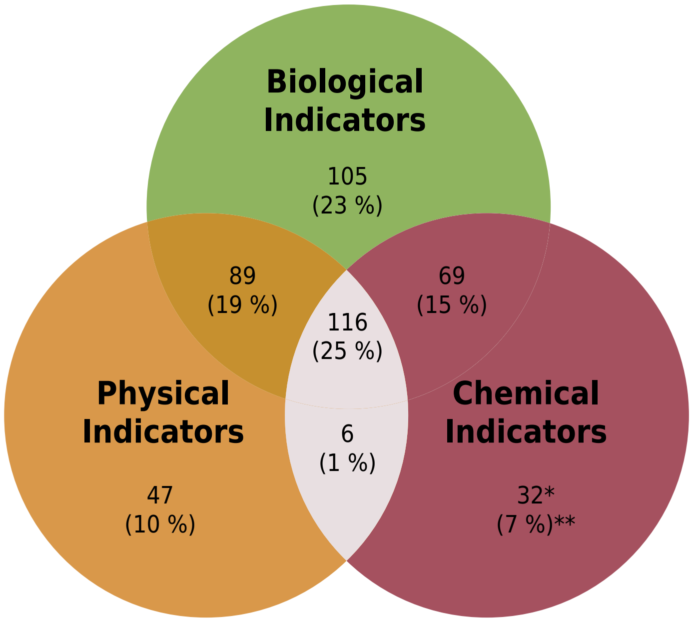


**Figure 7.** Venn diagram of the biological, chemical, and physical indicators showing the occurrence and intersections of using these indicators in papers after the first filter selection (n = 464), determined from 2014 to 2021. * Number of papers. ** Percentage corresponding to the number of papers. First Filter: studies carried out in Brazil, which mentioned at least one of the terms of interest ("*soil health*" or "*soil quality*" or "*qualidade do solo*") and that evaluated soil biological, physical, or chemical indicators, accessing at least one of them.

use simple methodologies with easy sampling and analysis, making the repeatability of the evaluation viable. This mostly justifies the higher frequency of using SOM parameters, phosphorus, and bulk density after using the second filter (Figure 6b). For Brazilian soils, the SOM is a key indicator for assessing soil quality, since it is essential to provide fertility to the soil, as the soil microbial activity, being highly related to all groups of soil quality indicators (biological, chemical, and physical) (Bünemann et al., 2018). Phosphorous stood out among the chemical indicators because most of the Brazilian soils hold a very high P adsorption capacity, resulting in low concentration in soils, restraining plant growth - unless it is supplied by fertilization and/or soil conservation management practices (Pavinato et al., 2020). The soil bulk density measurement is relatively fast and simple, with low cost and absence of sophisticate laboratory equipment (Hillel, 1982; Shukla, 2013). Soil bulk density is directly linked to many soil processes, such as soil compaction and water infiltration, and is also used in the calculation of other indicators such as total porosity and soil C stock.

Our results are in line with those reported by Bünemann et al. (2018) on a global scale, which clearly revealed a higher frequency of chemical indicators in soil quality studies, followed by physical and biological. Here, the biological indicators stood out, because differently from Bünemann et al. (2018), we considered SOM parameters as biological indicators due to their close relationship with soil biota and processes regulated by living organisms (Lal, 2015). Recent Brazilian soil quality studies have also included SOM parameters as biological indicators (*e.g.*, Cherubin et al., 2016b; 2021; Luz et al., 2019; Lisboa et al., 2019).

Our review also revealed that 40 % of the papers after the first filter evaluated exclusively indicators of one component of soil quality (23 % biological, 10 % physical, and 7 % chemical indicators), and 25 % of the studies (116) included all the three components together (Figure 7). We also observed that 19 % of papers considered biological and physical, 15 % considered chemical and biological, and 1 % evaluated chemical and physical soil attributes together.

Biological indicators were the mostly evaluated parameters being present in 83 % of papers in the first filter, mainly due to the group of indicators related to soil organic fractions, followed by physical (54 %) and chemical (48 %) indicators (Figure 7) (*n* = 464). If the group SOM parameters were removed, then the biological indicator group would have been presented in only 38 % of the papers (*n* = 464). It is worth mentioning once more that soil biological indicators are basically restricted to SOM-related indicators, thus, the insertion of a larger number of biological indicators (*e.g.*, ecological indexes of macro and mesofauna; microbial biomass, soil respiration, enzymatic activity, and soil DNA parameters) in the soil quality assessments is a priority area of research that should be deepened in the coming years.

Although 116 papers evaluated the three indicators: physical, biological, and chemical attributes (Figure 7), only 30 papers of the second filter performed soil quality assessment (Figure 7) integrating these indicators. This demonstrates the need for more studies aiming to assess soil quality in full essence. Many papers worked exclusively with one group of indicators being biological, physical, and chemical 105, 47 and 32, respectively (Figure 7). Despite this, these papers are important because they focus on explaining the impact of land use and management on specific processes, which are fundamental to advancing knowledge in soil science, but not in soil quality.

## CONCLUSIONS

Publications mentioning the term soil quality in Brazil have grown substantially in the last seven years. However, very few (less than 10 %) of these studies had focused on the soil quality assessment, including a comprehensive evaluation of soil chemical, physical and biological indicators in an integrated manner. Most of the studies (more than 90 %) only addressed specific soil attributes, or processes, and included the term soil quality in a broad context, not truly assessing soil quality. Thus, our study clearly showed that the broad context of the use of “soil quality” term causes lots of impacts, as a lack of precision when searching in scientific literature databases (such as *Web of Science*, *Scopus* and *Scielo*), aiming to find studies that evaluated soil quality.

Our review showed that there are still gaps to be filled to advance the Brazilian soil quality assessments scientifically (*e.g.*, defining indicators, methods of sampling and data analysis, interpretation curves, among others). We advocated that soil quality concepts should be further spread and popularized among students, researchers, farmers, consultants and politicians.

Furthermore, despite soil quality thematic has evolved in Brazil in the last few years, the creation of specific courses (extension, under and graduate) related to soil quality should be encouraged, as well as textbooks that could be useful for disseminating soil quality’s principles across the country.

## ACKNOWLEDGMENTS

We thank the team of extension group - SolloAgro (ESALQ/USP) that provided the scholarship for the first author during the specialization course.

## SUPPLEMENTARY DATA

Supplementary data to this article, containing information about the 464 papers which passed our first systematic selection, can be found online at https://www.rbcsjournal.org/wp-content/uploads/articles_xml/1806-9657-rbcs-46-e0210103/1806-9657-rbcs-44-e0210103-suppl01.pdf.

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