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Review Article

Slaughterhouse effluents and soil quality: A review

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A R T I C L E I N F O

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A B S T R A C T

The increased demand for food and water in a growing population leads to the need for sustainable food security strategies, in which the reuse of agro-industrial effluents may play an important role in addressing this challenge. However, only a few studies have focused on the impact of irrigation with slaughterhouse effluents on soil quality. Thus, this study aims to compile, classify, analyze, and discuss bibliometric data and soil quality assessments in studies on irrigation with slaughterhouse effluent. A bibliography research was conducted on the Web of Science and Scopus databases and a total of 29 records were selected and analyzed. Bibliometric aspects were evaluated and information about the methodological description of the experiment, the effluent and about soil quality was also extracted from the database. Australia, New Zealand, Brazil and Nigeria are the countries with the most publications from 1970 onwards, with the first two countries having scientific cooperation with each other. These studies assessed mainly chemical soil properties, from which total/available N, total/available P and exchangeable K the ones that most positively affected soil quality. Soil physical and biological indicators of soil quality were less frequently investigated and therefore further research is needed, since they contribute to the correct understanding of soil health and strategic decision-making aimed at maintaining crop productivity and ecosystem services provided by the soil.

1. Introduction

Water demand has increased about 1% annually due to population growth, leading to a rise in the volume of effluents generated [1–3]. In this context, many sectors compete for water resources, with crop irrigation being the largest consumer, which accounts for 70% of water use worldwide [4]. Wastewater application in crop fields has emerged as an alternative to decrease freshwater consumption in agriculture, providing nutrients, reducing the need for synthetic fertilizer, and serving as an environmentally friendly solution [5,6].

Slaughterhouses and meat processing industries require large amounts of water for processes such as slaughtering and cleaning, generating wastewater with potentially polluting characteristics [7–10]. Typically, such effluents have high concentrations for biochemical oxygen demand (BOD), organic matter, nitrogen, phosphorus, total suspended solids (TSS) and salts, along with substances such as ammonia, potentially toxic metals (PTM) and pathogens [11,12]. The composition of effluents from slaughterhouses and meat processing industries varies depending on the country, animal species and the number of animals slaughtered or processed [7,8,12,13]. Therefore, whether for disposal in water bodies or for agricultural use, the generated effluents need adequate treatment, wherein anaerobic treatment is one of the most recommended methods [11,14,15]. According to Menegassi et al. [16] and Vergine et al. [17], the biological treatment coupled to agricultural reuse constitutes a viable alternative for recycling water and minimizing costs with fertilizers. For this reason, establishing standards, guidelines and legislation for agricultural reuse is crucial, and in this context, the guidelines on water quality for agricultural purposes by the World Health Organization (WHO) and by the United States Environmental Protection Agency (USEPA) are extremely important [18,19].

To measure the benefits of wastewater reuse, it is of paramount importance to monitor soil quality (soil health), since a proper soil

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management promotes the functionality of ecosystem services provided by the soil and improve food security, a result of the satisfactory crop yields [20–22]. Soil quality is defined 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*" [23].

Several studies have shown that wastewater irrigation may change soil physical, chemical and biological conditions, including an improvement in soil fertility, although it may also lead to salinization and sodification [24,25]. Soil organic matter is often cited as the soil quality indicator most influenced by wastewater irrigation, which leads to a higher soil organic matter content [24,26,27]. However, there is a lack of studies about wastewater irrigation specifically with slaughterhouse effluent and its impact on soil quality. The few studies about that relate an increase in soil fertility and cation exchange capacity (CEC), changes in soil pH, increase in soil salinity and sodicity, as well as a reduction in soil bulk density in the topsoil [16,28–30].

Therefore, monitoring the published literature about irrigation with slaughterhouse effluent and its impact on soil quality is of primary importance to comprehensively understand the state of the art about this topic. The primary objective of this study is to systematically review and analyze the literature on the use of slaughterhouse effluent for irrigation and its impact on soil quality. Specifically, this study aims to: (i) gather and classify bibliometric data related to the topic, including information about institutions, countries, and authors involved in research on irrigation with slaughterhouse effluent; (ii) analyze and discuss the soil quality assessments conducted in the selected studies, with a focus on changes in physical, chemical, and biological soil properties due to wastewater irrigation; and (iii) map the state of the art in this area by synthesizing the findings from various studies and identifying knowledge gaps, trends, and potential research opportunities. By achieving these objectives, the study seeks to contribute to a deeper understanding of the effects of slaughterhouse effluent on soil quality and inform future research and practices regarding agricultural reuse of such wastewater.

2. Material and methods

A bibliographic search was conducted to build the bibliometric review by combining search terms and consulting the Web of Science - WOS (https://www.webofscience.com/) and Scopus (https://www.scopus.com/) databases. The search was performed by selecting the option "topic" in both databases, which considers title, abstract and keywords. The search terms were combined using Boolean operators as follows: ("slaughterhouse" OR "meat" OR "abattoir" OR "meatworks" OR "meat industry" OR "meat processing factory") AND ("effluent" OR "wastewater") AND ("soil quality" OR "soil health" OR "soil properties" OR "soil attributes" OR "soil" OR " soil nutrient*" OR "soil fertility"). The search led to 107 records in WOS and 234 in Scopus, which were retrieved on February 16th, 2025. The search was filtered to include only articles in English, resulting in 90 records in WOS and 154 in Scopus. This filtering step included papers with an abstract in English, even if the full manuscript was in another language. All possible publication years were considered. The steps related to searching and sorting the articles were summarized in Fig. 1.

The first step in data triage was to combine records from both databases and merge duplicates. In order to do so, the R package "bibliometrix" was used in the RStudio® environment, which resulted in an output file containing 175 records and their associated information in the xlsx format. Thereafter, dataset filtering (article selection) was performed following two criteria: only records studying slaughterhouse effluent and concurrently assessed the impact of the effluent application on any physical, chemical or biological soil property. This step was completed by three reviewers and resulted in a total of 29 records selected. Although a higher number of records were found after database union, many of them were not considered because: (a) there was no assessment of soil quality indicators, (b) there was no slaughterhouse effluent, or (c) there was no data related to chemical and physical characterization of the applied effluent.

After article selection, the following bibliometric data was extracted from each record: publication year, citation rate by year, number of records by journal, number of records by institution, keyword co-occurrence, number of records by country, and co-authorship between countries. The resulting data was processed by using the software Microsoft Office Excel (version 2019) and VOSviewer (version 1.6.18), in which the latter was used for bibliometric mapping considering the data for co-authorship, co-citations, citations, keyword co-occurrence and bibliographic coupling [31].

In addition to the bibliometric data, information about the experimental methodology, effluent characteristics and about soil quality was also extracted from the database. This includes the experimental conditions, physicochemical properties of the effluent, methods of effluent treatment, crops irrigated with slaughterhouse effluent, soil order, soil texture, soil depth, chemical, physical, and biological indicators of soil quality, as well as the impact of irrigation with slaughterhouse effluent on soil quality.

3. Results and discussion

3.1. Bibliometric data: publication years, authors, journals and institutions

The first paper about irrigation with slaughterhouse effluent and its impact on soil quality was published by Wells and Whitton in 1970 [32]. It is important to mention that all possible publication years were considered in this search, and therefore the earliest record is from 1970. A total of 29 articles were published by 2025, averaging less than an article per year (Fig. 2). The year with the highest number of articles was 2017, with four papers published, including Oliveira et al. [33,34], Luchese et al. [35], and Matheyarasu et al. [36], as listed in Supplementary Table 1.

The number of citations within the studied database is shown in Fig. 3. The most cited article is the one from Abegunrin et al. [2], which assessed soil-plant systems with three types of wastewater (cassava effluent, abattoir and bathroom wastewater) and two crop species (eggplant and spinach). The high impact of this article relies on the great potential of effluent reuse, especially from slaughterhouses, as its application boosts soil fertility and enhances crop yield, although there might be risks associated with it, such as soil salinization and sodification. Other risks and opportunities, such as an increment in nitrous oxide (N_2O) emission and recovery of soil total nitrogen, are also reported in the top-cited publications [2,37,38].

The work of Menegassi et al. [16], which was cited 22 times, is of great importance. The authors report on the impacts of applying slaughterhouse effluent on pasture growth, soil fertility and mention the possibility of a complete replacement of nitrogen fertilization due to high concentrations of nitrogen in the effluent. Therefore, it is notable that this research topic is of great importance and hence soil quality assessments in areas where agro-industrial effluents are applied should be further studied, especially areas with slaughterhouse effluent.

Regarding the number of records by journal, there is no clear trend, and the papers are well-distributed between journals (Fig. 4). However, it is important to mention that the journals "Bioresource Technology", "New Zealand Journal of Agricultural Research" and "Water, Air, and Soil Pollution" have a total of three published papers each. Nevertheless, the most cited paper [2] was published in "Catena".

By analyzing the bibliographic coupling, which assesses the similarity between records from their cited references [39,40] it is evident that only 8 out of the 29 papers share citations (Fig. 5). These shared citations occur among papers from the same authors, with the highest number of shared references -three – found between studies by Oliveira et al. [33,34]. Such outcome suggests a lack of connection between

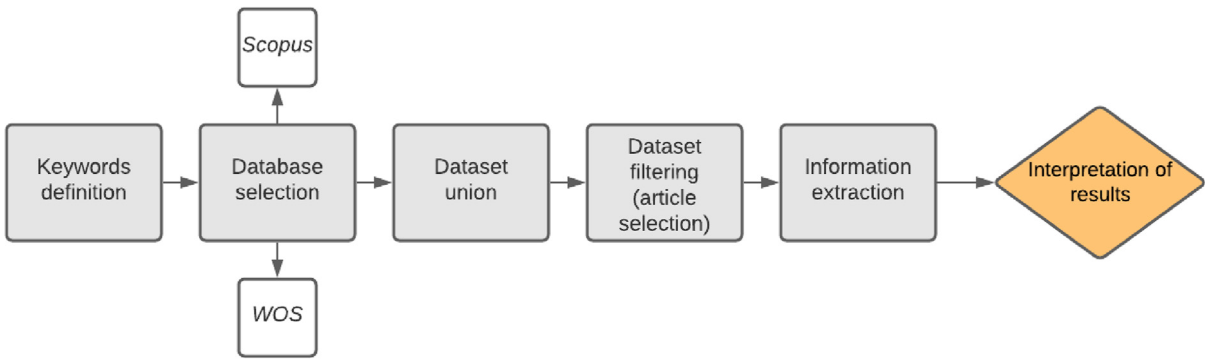

Fig. 1. Steps related to selecting, sorting and interpreting articles and the associated information within the database.

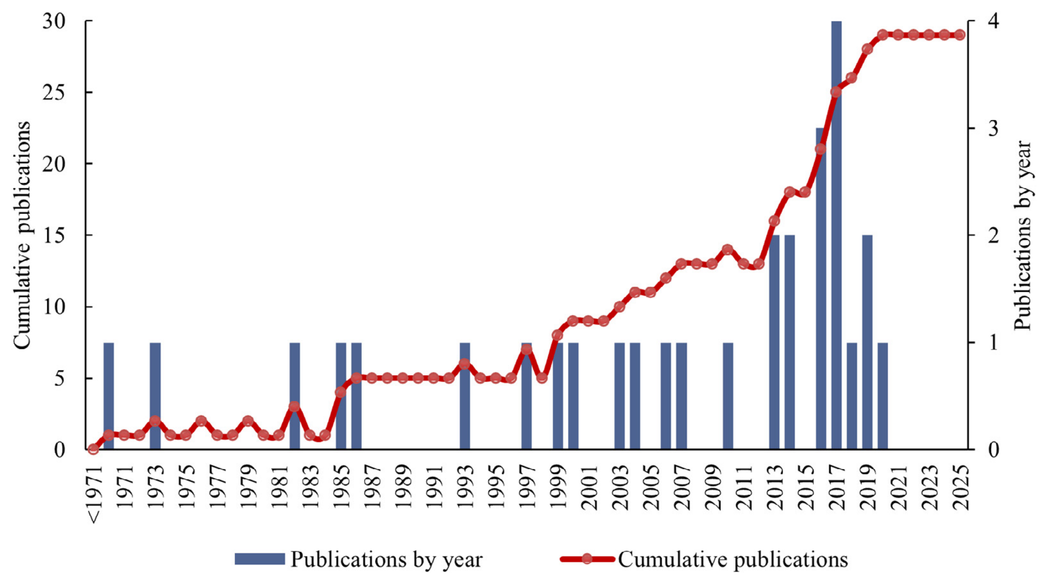

Fig. 2. Number of publications by year related to studies about irrigation with slaughterhouse effluent and its impact on soil properties (n = 29). Data retrieved on February 16th, 2025.

research centers that study irrigation with slaughterhouse effluent and its impact on soil quality.

The co-occurrence of keywords analyzes their frequency and connections within the database to identify key research topics and trends [41,42]. From the 29 records reviewed in this work, 398 keywords were retrieved. From this total, considering those with at least four occurrences, two clusters can be noted from the co-occurrence map (Fig. 6). The terms "soil", "irrigation", "wastewater", "soil properties", "effluent", "nitrogen" and "slaughterhouse" occurred with the highest frequency and connection, in which the term "soil" is placed in the central portion of the map. The green cluster consists of terms related to soil properties and their connection with effluent, while the red cluster is connected to terms related to irrigation and wastewater treatments from slaughterhouses.

3.2. Countries and co-authorship

New Zealand and Australia are the countries with the most published articles in this review's dataset, accounting for 31 and 24% of the total, respectively. These countries collaborate with institutions from the United Kingdom, Canada and South Korea. Brazil (21% of publications) and Nigeria (17%) are also main publishing countries; however, with fewer international connections, with Brazil only linked to Spain (Fig. 7).

Institutions from Australia and New Zealand are the most prominent in terms of funding studies about irrigation with slaughterhouse effluent and its impact on soil quality (e.g. University of South Australia). Furthermore, 23 institutions were listed within the 29 papers studied in this review, suggesting that there is no leading institution studying this topic.

This scattered institutional involvement reflects the global relevance of wastewater reuse, particularly in major beef-producing countries like Brazil and Australia [11,43,44]. In 2023, beef production reached 11 million tons in Brazil and 2 million tons in Australia [45]. Additionally, the demand for water in pasture irrigation and for fertilizers has increased alongside the expansion of the agricultural sector in both countries [16,36], presenting significant opportunities for wastewater reuse. Similarly, irrigated areas in New Zealand increased about 90% over the last 15 years [46], and the use of slaughterhouse effluent for irrigation is both permitted and commonly practiced in the country [28,47,48].

Beyond these leading producers, wastewater reuse is also critical in water-scarce regions. Although Nigeria is not widely recognized for its agricultural sector, its arid climate in some areas leads to frequent water shortages, directly affecting agriculture. In this context, wastewater reuse could play a vital role; however, Nigeria currently lacks specific legislation regulating agricultural reuse and its impact on soil quality [2].

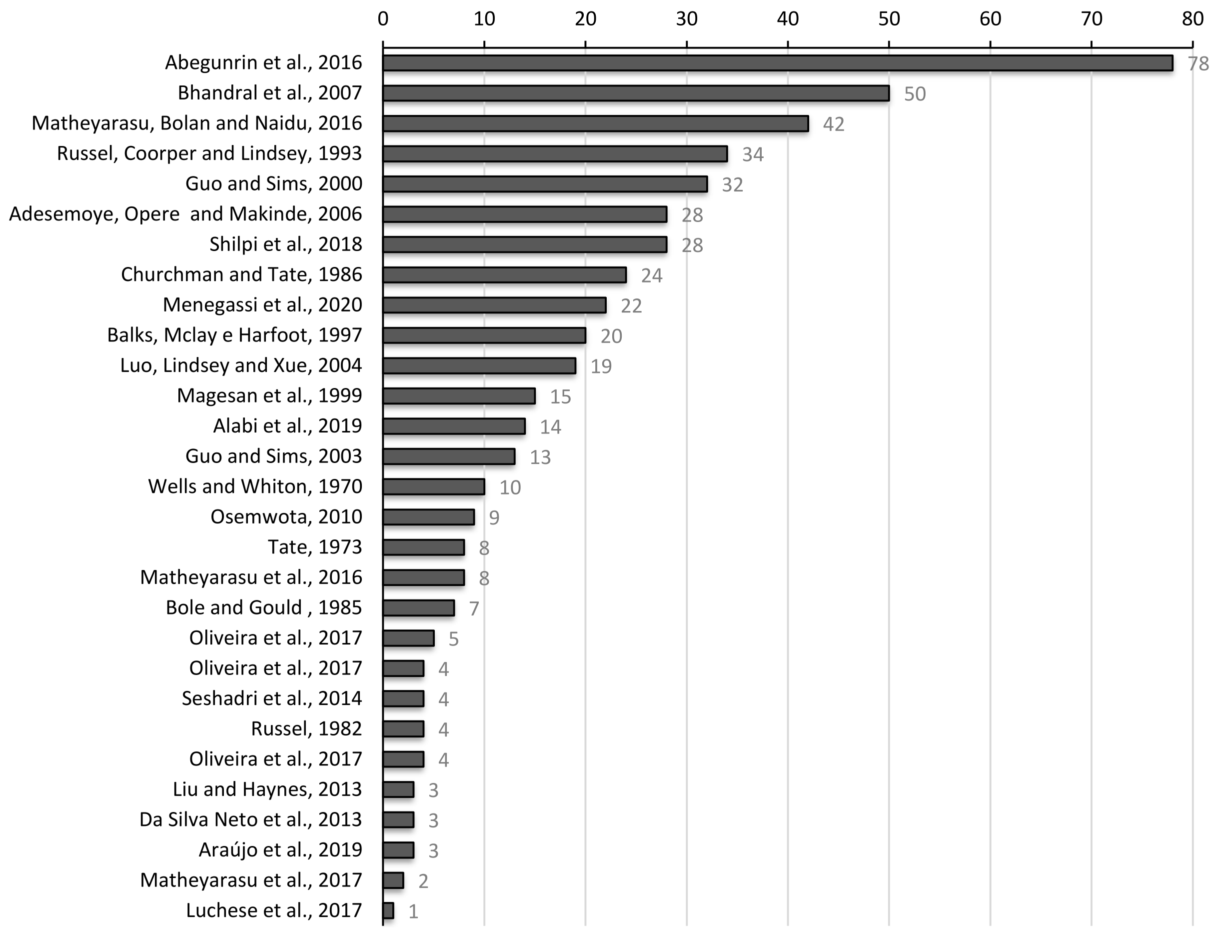

Fig. 3. Number of citations within the studied database (n = 29) as of February 16th, 2025.

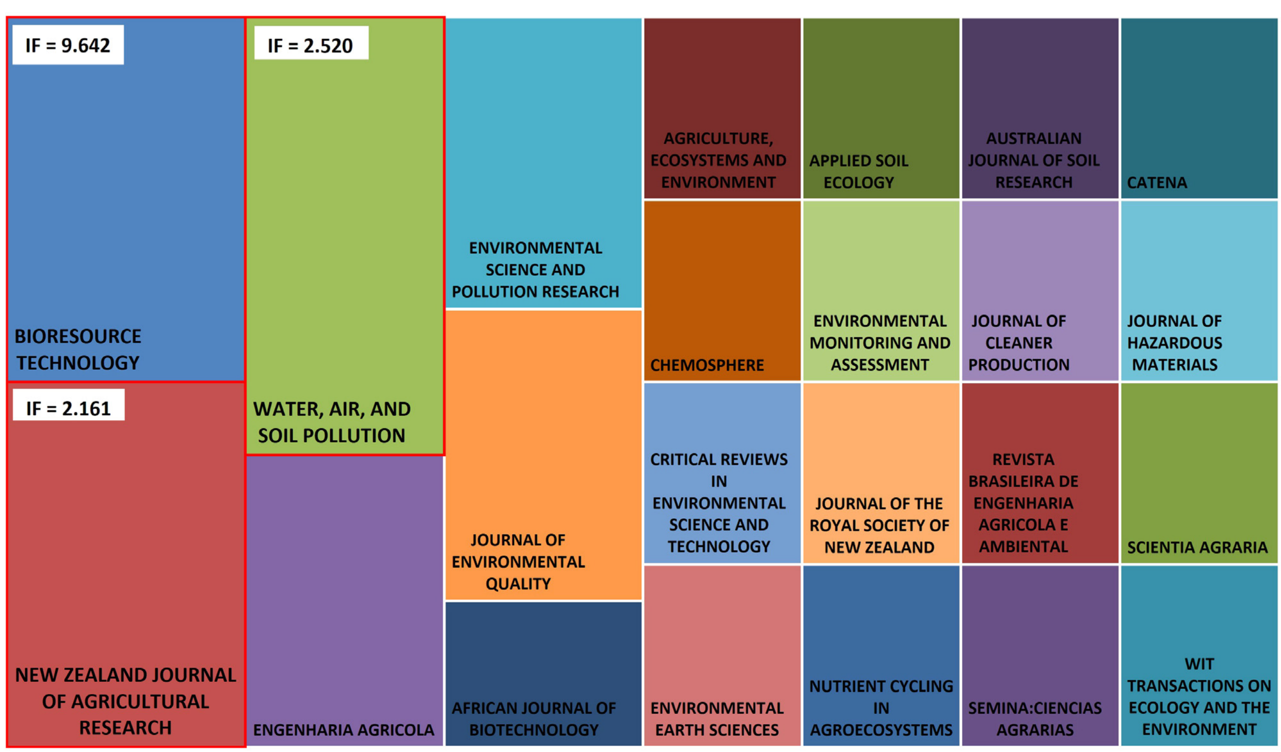

Fig. 4. Number of publications by journal within both Scopus and Web of Science (IF = Impact Factor).

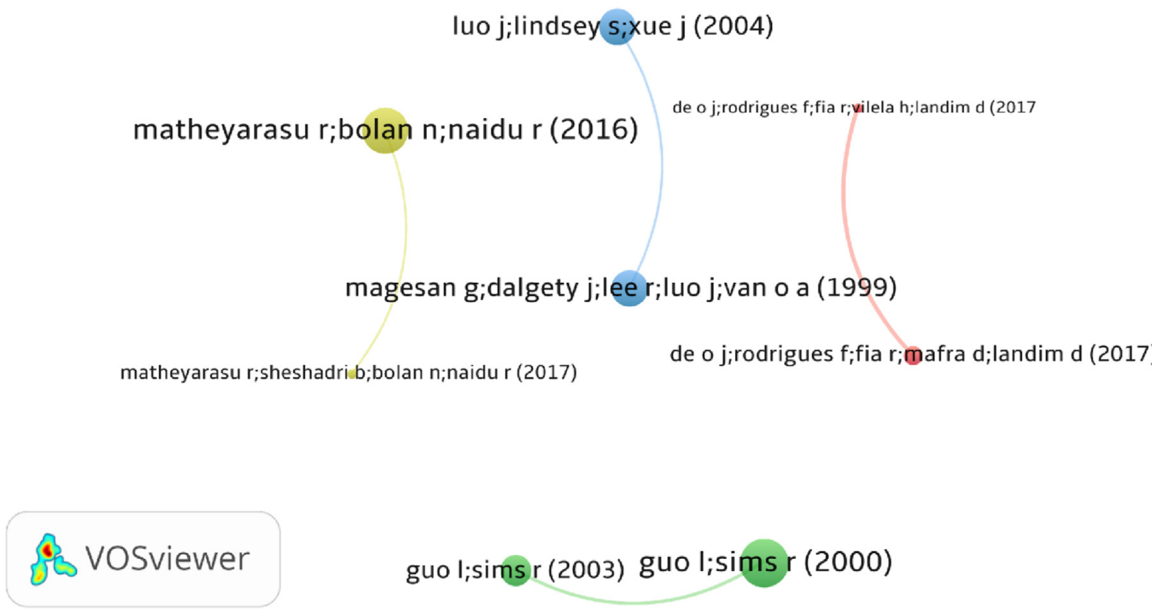

Fig. 5. Map of bibliographic coupling from records with bibliographic connections between them (n = 8). The size of a circle is related to the number of works cited in a paper and the line weight connecting circles is related to the number of citations shared between papers.

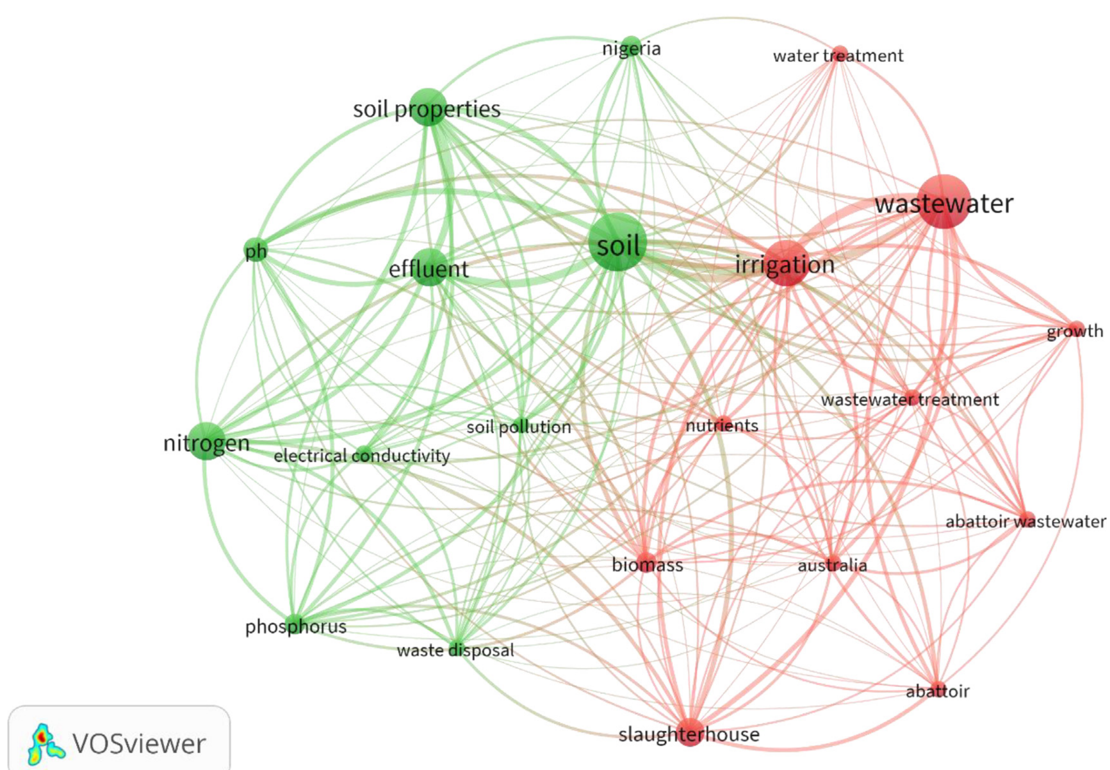

Fig. 6. Map of co-occurrence of keywords, considering a minimum frequency equal to four. The size of a circle is proportional to the number of citations in records and the line weight is related to the number of connections between keywords.

3.3. *Experiment type, effluent treatment and cultivated crop*

The reviewed articles applied different methodological approaches to assess the impact the slaughterhouse effluent application had on soil quality. Among the 29 works, 15 used field experiments, six were carried out in pots, three in soil columns, and five in areas where the effluent was applied but there was no experimental plot (please see Supplementary Table 2). Most publications reported physicochemical properties of the applied effluent (please see Supplementary Table 3), without mentioning the irrigation method used to apply slaughterhouse effluent, only citing the total water depth.

Regarding the effluent treatment (Fig. 8), most publications reported the use of biological treatment (41%), followed by preliminary treatment (31%), no treatment mentioned (24%) and other types of treatments (10%). Biological treatment, which can be further divided into aerobic and anaerobic systems [14], is considered the most suitable

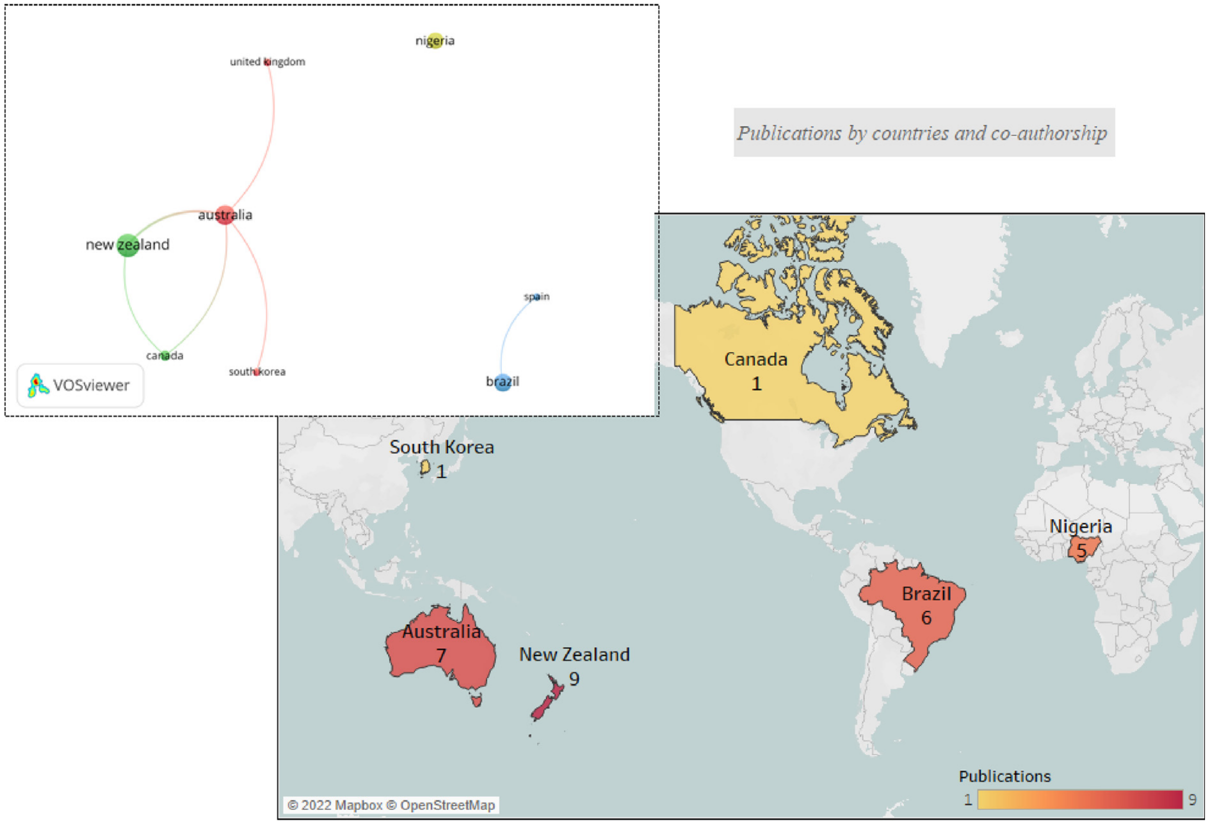

Fig. 7. Bibliometric map for co-authorship between countries and the number of publications by country. The size of a circle is proportional to the number of publications by country and the line weight is related to collaborations between countries.

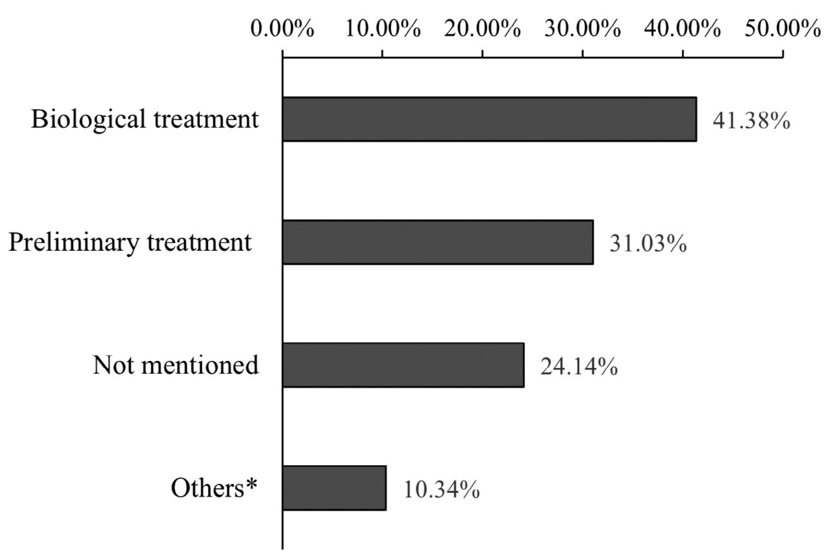

Fig. 8. Frequency of treatment type used in the slaughterhouse effluent from 29 reviewed publications. *Others: physicochemical treatments, direct application into the soil and solution using moringa seeds.

method for treating slaughterhouse effluent due to its high capacity to remove organic matter and nutrients [49,50]. Furthermore, anaerobic systems are preferred for their higher treatment efficiency, lower complexity, reduced sludge production and the potential to produce biogas - methane [7,11].

In relation to crops (Fig. 9), most works assessed the application of slaughterhouse effluent on pasture (34%) and forages (28%), suggesting a great potential for reuse in crops grown for animal feed. In addition, 24% of works did not assess any plant species.

The result of most works assessing the impact of applying slaughterhouse effluent on crops intended for animal and non-human food might be related to the lack of clear legislation. While research about agricultural reuse has gained attention due to climate change and water shortages, the associated legislation is still poorly defined. The guidelines suggested by the World Health Organization (WHO) and by the United States Environmental Protection Agency (USEPA) are of primary importance, as they provide reference values for water quality

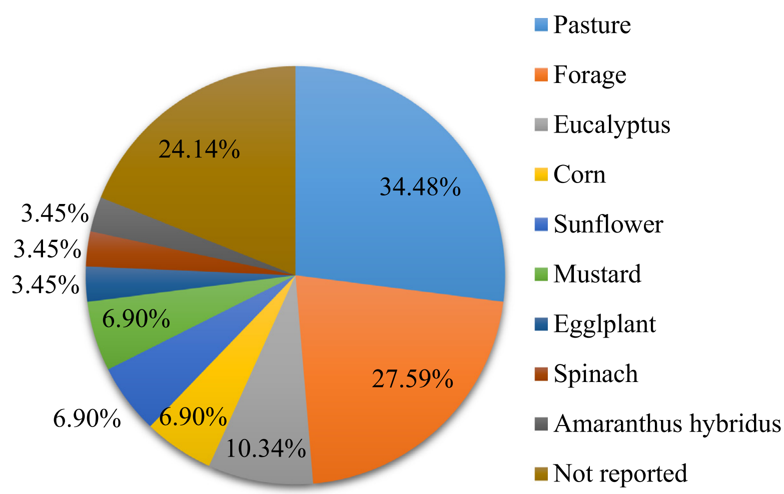

Fig. 9. Frequency of crops assessed in publications related to the application of slaughterhouse effluent and soil quality (n = 29). Please note that a single paper may have evaluated multiple crops, so the total in the graph may exceed 100%.

assessments [51,52]. However, most guidelines warn about the risk of bacterial contamination when wastewater is used in food crops [53].

Considering legislation about wastewater, Brazil issued the resolution Conama 503 on December 14th, 2021, which "*defines criteria and procedures for wastewater reuse in fertigation systems with effluents from food, beverage and dairy industries, slaughterhouses and rendering plants*". As Brazil is one of the main countries studying soil quality in soils irrigated with slaughterhouse effluent, this recent resolution may create opportunities for wastewater reuse in other crops rather than pastures. The resolution establishes tolerance limits for *E. coli* in agro-industrial effluents for irrigated food crops in which the edible part is in contact with the soil. Another important contribution is the establishment of criteria/parameters to monitor and characterize soils before and after the application of agro-industrial effluents, such as pH, electrical conductivity, organic matter, P, K, Ca, Mg, Al, S, Na, B, Cu, Fe, Zn, Mn, soil texture and soil water infiltration.

3.4. Soil classification and soil quality indicators

18 out of the 29 reviewed papers mentioned the soil order [54], which led to 11 papers (38% of papers) without soil classification. Within the 18 papers, 20 soils were classified in the following orders: Andisols (30%), Inceptisols (20%), Oxisols (20%), Alfisols (10%), Entisols (10%), Mollisols (5%) and Vertisols (5%). All Andisols were in New Zealand and had either silt loam or sandy loam texture. Although Andisols cover only 1.8% of the Earth's land mass, they have been used for generations, and conservation practices have been installed in most cases [55]. Similarly, all the Inceptsols were also from New Zealand. In contrast, Oxisols were located in Brazil, and all of them were clayey soils, typically strongly aggregated in fine and very fine granular structures [55], which results in rapid permeability.

In the reviewed database, 31% of the papers did not mention soil texture, [30,36,37,44,56–60] 28% studied sandy loam soils [2,28,38, 61–65], 14% focused on silt loam [48,66–68], 10% on clayey soils [16,33,34], 10% on sandy soils [69–71], 3% on clay loam [35] and 3% on loamy sand [64]. The work of Oliveira et al. [33] investigated leaching through soil columns of a clayey Oxisol and found a significant nitrate leaching when wastewater from a swine slaughterhouse was applied. Similarly, Matheyarasu et al. [44] highlighted nitrate leaching in groundwater as a potential water pollutant and suggested the use of nitrogenous inhibitors and efficient farm budgeting to improve nitrogen management and to contribute to a more sustainable agriculture. Seshadri et al. [72] recommended the use of flyash and redmud as alkaline industrial by-products to reduce P leaching after studying columns of sandy soils irrigated with slaughterhouse wastewater.

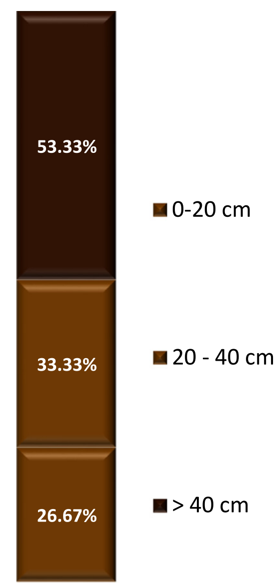

Fig. 10. Soil depth most frequently assessed from experimental plots in fields (n = 15).

Regarding the soil depth studied, within the 15 papers with field experiments, 53% assessed soil properties down to 20 cm, and 33% between at a depth of 20–40 cm (Fig. 10). This is because nutrients strongly cycled by plants are more concentrated in the topsoil, and therefore it is the soil layer commonly sampled for soil fertility assessments [73]. Only a few studies assessed soil quality indicators deeper than 40 cm [36,48,59,64].

In relation to the frequently assessed soil quality indicators within the database (n = 29 papers), most were chemical indicators (Fig. 11), with soil pH being the most assessed (69%). Among physical indicators, the most assessed was soil bulk density (17%). Regarding biological indicators of soil quality, the only two assessed indicators were microbial respiration and microbial diversity, each of them present in 7% of the papers. It is important to mention that only indicators present in at least two publications were considered for Fig. 11.

As reported by Bunemann et al. (2018), chemical indicators of soil quality are usually more frequently assessed in relation to physical and biological indicators. In the context of soils irrigated with slaughterhouse effluent, the prevalence of chemical indicators may stem from

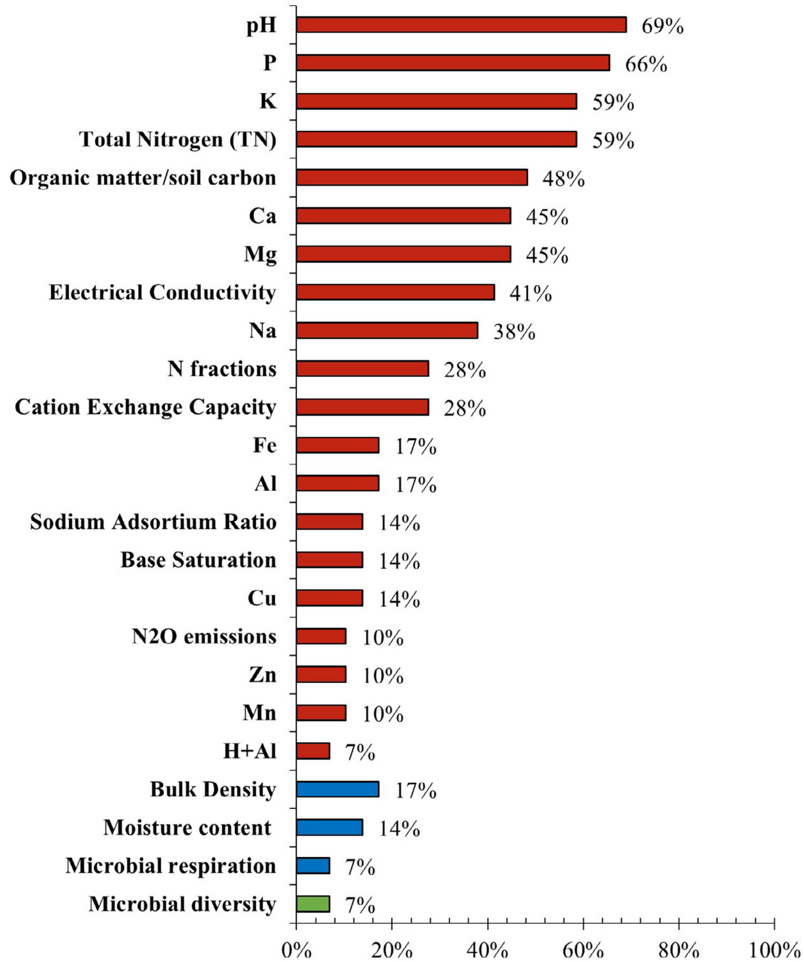

Fig. 11. Frequency of appearance of chemical, physical and biological indicators (respectively in red, blue and green) in the publications evaluated in the database.

the high nutritional load in the effluents, which directly influences soil fertility. Overall, 86.1% of papers assessed chemical indicators, 41.3% physical indicators and 27.5% biological indicators (Fig. 12). The work of Seshadri et al. [72] was the only one that assessed chemical, physical and biological indicators of soil quality. The most frequent combination between soil quality components (chemical, physical and biological) was between chemical and physical (31.3%) as assessed in the works of Shilp et al. [60], Matheyarasu et al. [36] and Seshadri et al. [72]. No work assessed soil quality by building or evaluating an analytical soil quality index.

3.5. Impact of irrigation with slaughterhouse effluent on soil quality

According to the frequency of soil quality indicators (Fig. 11), the three macronutrients that were most positively impacted from the application of slaughterhouse effluent were related to soil P (15 studies), soil N (10 studies) and available K (8 studies), as shown in the Supplementary Table 2. This is related to high concentrations of organic matter and these nutrients in slaughterhouse effluents, as previously mentioned [30,65,69]. Regarding soil P, significant increments of its content were reported in layers of 0–30 cm [57,69], 5–35 cm [36] and 0–40 cm [16], as well as when a control treatment was applied, that is, irrigated with tap water [16,36,60,71].

Similarly, nitrogen concentrations (total N and available N) also increased in the layers of 0–10 cm [57] and of 0–40 cm [34,36,69] as the application rate of slaughterhouse effluent increased [34,60], being higher than control treatments, which were irrigated only with tap water [30,33,36,71]. Some works reported an increase in N_2O emissions due to denitrification, which is related to the availability of mineral N and the lability of C in slaughterhouse effluents [37,44,63]. Similar outcomes can be observed for the increased concentration of K from irrigation with slaughterhouse effluents.

The reviewed database showed varying results for the exchangeable bases Ca and Mg. However, their concentration decreased when Na^+ concentration increased [48,57,69]. Higher concentrations of Na in slaughterhouse effluents may lead to Na accumulation in the soil, even in the subsoil through leaching [16,48,57] and contribute to Ca^{2+} and Mg^{2+} displacement [74]. The increase of Na^+ concentration may also lead to clay dispersion, reducing the soil physicochemical quality and the water availability to plants [75]. Such increase in $Na^{\underline{+}}$ concentration was reported by six works within the database [16,34,48,57,65,66], followed by increases in the percentage of exchangeable sodium [48,57] and in sodium adsorption ratio (SAR) [2]. The increment of electrical conductivity was reported by six works in the database [34,36,57,60,71,72], which was mainly due to the increase of K^+ and Na^+ concentrations.

Regarding soil pH, nine studies reported a decrease following slaughterhouse effluent application [28,35,36,38,57,69,70,72] while three others reported an increase in soil pH [34,62,71]. Most works relate such decrease in soil pH with oxidation of organic compounds and with the lower pH of the applied effluent [36,38], as well as the process of nitrification, which releases ions of H [28,70]. Considering other chemical properties as the micronutrients Fe, B and Mn, the works of Matheyarasu et al. [36], Seshadri et al. [72] and Osemwota [71] were the only three that reported positive results after the application of slaughterhouse effluents. Similarly, the works of Alabi et al. [69],

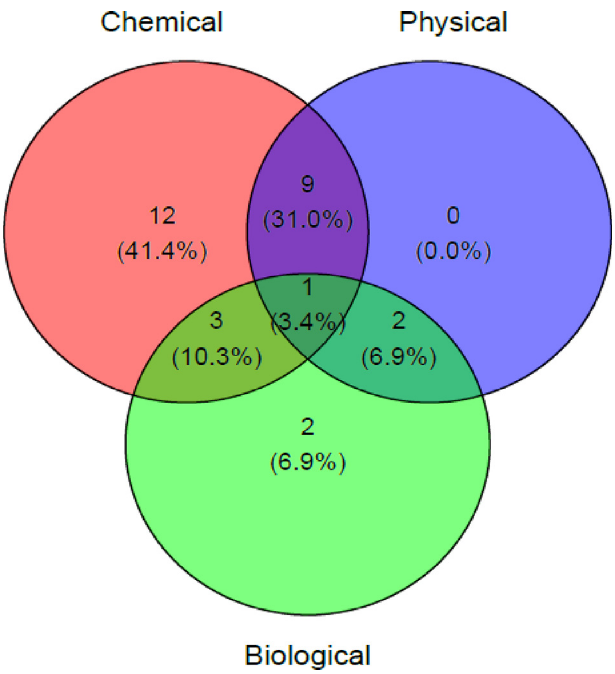

Fig. 12. Percentage and total count of studies that assess chemical, physical and biological indicators of soil quality (n = 29).

Abegunrin et al. [2] and Wells and Whitton [32] were the only three that reported positive impacts for CEC. No significant impact was found on the remaining chemical properties when slaughterhouse effluent was applied.

As previously mentioned, soil physical and biological properties were poorly investigated in the reviewed papers. The works that reported a positive impact on soil organic matter/soil carbon attributed the results to the large addition of soluble organic matter from the slaughterhouse effluent into the soil [28,32,57]. Such an increase in SOM may lead to an increase in soil microbial biomass, soil basal respiration, bacterial and fungal diversity and the microbial metabolic quotient [57,67,76]. Other studies reported an increase in the enzyme activity for acid phosphatase [72] and the increase in the number of earthworms in the soil [68].

Although Guo and Sims [28] attributed the decrease of soil bulk density to the increase of SOM, the work of Alabi et al. [69] found that the irrigation with slaughterhouse effluent decreased SOM in the subsoil and caused soil compaction in the topsoil due to high soil moisture. A temporary reduction of soil permeability due to the formation of bacterial biofilm was reported by Balks et al. [67], although Alabi et al. [69] reported an increase in saturated soil hydraulic conductivity. Nevertheless, the trend is that the application of treated slaughterhouse effluent influences SOM, which in turn impacts soil bulk density and soil aggregation [28,68].

4. Conclusions

The reuse of slaughterhouse effluents for irrigation presents both opportunities and challenges for soil quality. The bibliometric analysis revealed that research on this topic is limited, with only 29 studies published in the past five decades. Despite increasing concerns over water scarcity and the need for sustainable agriculture, slow progress suggests challenges such as regulatory restrictions, environmental concerns, and effluent management complexity. Australia, New Zealand, Brazil, and Nigeria are leading contributors, with strong international collaborations from the first two countries.

Chemical indicators of soil quality were commonly assessed, with effluent application often increasing nitrogen, phosphorus, and potassium concentrations. These findings highlight the potential for enhancing soil fertility, reducing synthetic fertilizer use, and supporting sustainable agriculture. However, risks such as increased sodium concentrations, salinization, and sodification were also observed, which could affect soil permeability and aggregate stability. Soil pH responses varied depending on effluent composition and application rates. Physical and biological properties were underrepresented, despite their importance for soil quality. Some studies suggested effluent irrigation could increase organic matter, enhancing microbial activity and soil structure, while others pointed to issues like soil compaction and bacterial biofilm formation. More research is needed on the long-term impacts of effluent irrigation on soil structure and microbial communities.

A key issue identified was the lack of standardized methodologies, which hinders comparisons and generalizations across studies. Future research should aim to develop a comprehensive soil quality index for effluent-irrigated soils, integrating chemical, physical, and biological indicators. Furthermore, legislation plays a vital role in determining the feasibility of effluent reuse in agriculture. While some countries have established guidelines, others lack clear regulations, which may limit broader adoption. The recent Brazilian Conama 503 resolution is a significant step forward and could serve as a model for other regions to promote effluent irrigation while ensuring environmental and food safety.

CRediT authorship contribution statement

Lisiane Brichi: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Gustavo Pereira Valani:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Gabriela Pittoli Lyra:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Tamara Maria Gomes:** Writing – review & editing, Visualization, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Fabrício Rossi:** Writing – review & editing, Visualization, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.grets.2025.100207.

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