A CIRCULAR ECONOMY INVESTIGATION INTO TREATMENT TECHNOLOGIES AVAILABLE FOR THE DISPOSAL OF SLAUGHTERHOUSE DERIVATIVES

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ABSTRACT

Two major problems challenge the world of food today: the constantly growing demand for meat products and dealing with the volumes of waste produced by the industry. The volume of slaughterhouse derivatives produced when generating meat products threatens the health of humans and the environment. The need to feed a growing population sustainably and to find more sustainable and circular alternative treatment technologies for handling and disposing of slaughtering derivatives undoubtedly creates opportunities for several role players. A comprehensive bibliometric analysis was undertaken to identify such processes, considering the different slaughterhouse derivatives generated by red meat and poultry slaughterhouse facilities. The literature search and refinement process identified 130 scientific documents for analysis. The results highlight an increase in the scientific literature on the sustainable recovery of slaughterhouse derivatives, and a diverse range of available treatment technologies to dispose of such derivatives.

OPSOMMING

Twee groot probleme daag die voedselindustrie tans uit: die voortdurend groeiende vraag na vleisprodukte, en die hantering van die volumes afval wat deur die bedryf geproduseer word. Die volume slaghuisafgeleide produkte wat tydens die generering van vleisprodukte geproduseer word, bedreig die gesondheid van mense en die omgewing. Die behoefte om 'n groeiende bevolking volhoubaar te voed en om meer volhoubare en sirkulêre alternatiewe behandelingstegnologieë te vind vir die hantering en wegdoen van slagafgeleide produkte skep ongetwyfeld geleenthede vir verskeie rolspelers. 'n Omvattende bibliometriese ontleding is onderneem om sulke prosesse te identifiseer, met inagneming van die verskillende slaghuisafgeleides wat deur die rooivleis- en pluimveeslaghuisfasiliteite gegenereer word. Die literatuursoektog en verfyningsproses het 130 wetenskaplike dokumente vir ontleding geïdentifiseer. Die resultate beklemtoon 'n toename in die wetenskaplike literatuur oor die volhoubare herwinning van slaghuisafgeleides, en 'n diverse reeks beskikbare behandelingstegnologieë wat beskikbaar is om van sulke afgeleides ontslae te raak.

1. INTRODUCTION

Owing to a constantly growing population, the global rate of meat consumption is skyrocketing [1]. The increase in demand for meat products creates the need for an enormous quantity of resources. This challenges the role players in the industry because of the limited availability of natural resources, ongoing climate change, and food-feed-fuel competition [2].

The red meat and poultry industry is probably one of the fastest-growing meat industries [3]. The increased consumption of meat and meat-related products has contributed to the expansion of the red meat and poultry slaughterhouse industry, and thus to an increase in the number of slaughtering derivatives generated through slaughterhouses [4].

'Slaughterhouse waste' refers to the products that remain after the production of the principal commodity in slaughterhouses (the meat), and essentially comprises inedible offal and fats [4]. However, terms such as 'slaughterhouse waste' and related terms such as 'offal', 'by-products', and 'co-products' are sometimes used interchangeably [5]. Therefore, in this article, the term 'slaughtering derivatives' refers to all of the terms mentioned above except for the primary commodity, meat.

In slaughterhouse facilities, the handling of deceased animals and of slaughtering derivatives such as blood, stomach contents, and intestines has always been and continues to be an issue [6]. Improper management of slaughtering derivatives – for example, discharging them into waterways – not only poses a significant challenge to effective environmental management, but is also associated with decreased air, water, and soil quality and with several infectious agents that can be pathogenic to humans because of the high loads of nitrogen and phosphorus, odorous compounds, heavy metals, antibiotics, and pathogenic micro-organisms they contain [7], [8], [9], [10].

Aside from proper abattoir housekeeping, solid and effluent derivatives from slaughtering operations, including specific risk materials (SRM), must be handled, transported, and disposed of in accordance with the relevant regulations and in a way that is acceptable for each processing site [7].

The notion of a circular economy has been debated since 1970 [11]. The concept is commonly acknowledged as a strategy that promotes the shift from a linear consumption approach (the take-waste-dispose method) towards more sustainable, circular routes in which the waste – or, in this case, slaughtering derivatives – is reused and recycled, and so put back into the process or into other processes in different industries, resulting in a reduction in the use of raw materials [12], [13]. In a circular system, the essence of value creation lies in the opportunity to extract additional value from materials by cascading them through other applications [14]. A requirement to find more sustainable and circular alternative treatment technologies for handling and disposing of slaughtering derivatives undoubtedly creates opportunities for several role players.

Several good practices for the disposal and use of slaughtering derivatives are proposed in the literature and, when used, can reduce their environmental impact while possibly increasing the availability of value-added goods. Numerous 'new' technologies circulate the materials back into the economy through value-creation [15]. Given the extensive body of literature available on the different technologies, it is of great value to study the characteristics of some of the most common treatment technologies, and to research such technologies through the method of bibliometrics.

Bibliometrics is an effective and practical method for analysing academic research outputs and coping with large amounts of data [16]. According to [17], bibliometrics is considered one of the most effective ways of researching libraries of published material. Thus, the main objective of this review article is to collect state-of-the-art knowledge about research hotspots, frontiers, and trends in the current slaughterhouse industry through a comprehensive bibliometric analysis. Therefore, the review aimed to systemise and analyse the literature on treatment technologies for handling and disposing of slaughterhouse derivatives, with the ultimate goal of paving the way for future circular economy opportunities.

2. METHODOLOGY

Alan Pritchard introduced the bibliometrics method in 1969 [18]. The technique is known for reasonably evaluating the impact or value of research accomplishments [18]. It is a valuable tool that uses a combination of statistical and mathematical methodologies to map any changes in specific research fields [18].

The method employed to explore the literature about the different mature and emerging treatment technologies used for slaughterhouse derivatives consists of five stages, as shown in Figure 1.

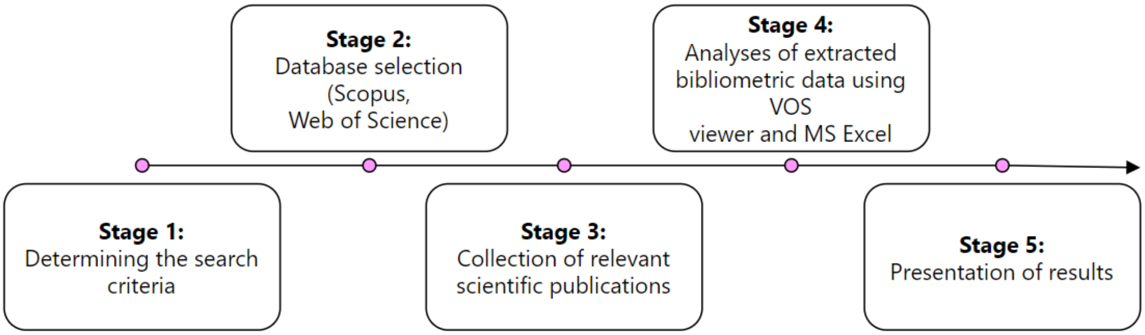

Figure 1: The five stages of a bibliometric analysis

Before exploring both the research and the industry literature, it was necessary to determine the research questions to be answered through the analysis. The research questions (RQ) of the analysis were as follows:

1. What is the output and growth trend of publications on the treatment and use of slaughtering derivatives?
2. Which keywords are most often used in the analysed scientific publications?
3. Which treatment technologies are most commonly used for handling and disposing of slaughtering derivatives in different countries?

Previous investigators from a range of fields have used equivalent methodologies to those used in this article for the successful execution of comprehensive bibliometric analyses [19], [17], [18], [20], [21].

2.1. Stage 1: Search criteria

The first requirement of the analysis was that it be based on scholarly publications that had investigated the slaughterhouse and abattoir industry and, more importantly, the handling or treatment of slaughterhouse derivatives. Therefore, a structured keyword-based search was used to identify and collect relevant documents that mapped the academic landscape that has focused on these central concepts. Three search levels were applied consecutively for the structured keyword-based search, as shown in Table 1.

Each search level had its own keywords. The keyword condition was used for two specific reasons: first, to ensure that the scientific literature fell within the scope of the study; and second, to ensure that the study did not deviate from the primary research questions identified earlier. Hence, numerous keywords, synonyms, and plural forms were used for each search level. A comprehensive listing of all of the search terms applied at each level can be found in Table 1. All of the search terms in each search level were connected with the Boolean "OR", and each search level was connected to the next search level with the Boolean "AND".

Table 1: Search levels for scientific literature, search word categories, terms, and results

Search level		Search terms	Scopus results	Web of Science results
1	Industry	TITLE-ABS-KEY (“Slaughterhouse” OR “abattoir” OR “slaughterhouses” OR “abattoirs”)	9 994	8 072
2	Slaughterhouse derivatives	(TITLE-ABS-KEY (“Slaughterhouse” OR “abattoir” OR “slaughterhouses” OR “abattoirs”) AND TITLE-ABS-KEY (“Abattoir waste” OR “livestock and slaughterhouse waste” OR “by-product” OR “by-products” OR “poultry waste” OR “red meat waste” OR “blood” OR “manure” OR “hides” OR “hide” OR “hooves” OR “trimmings” OR “trimming” OR “skin” OR “skins” OR “effluent” OR “effluents” OR “intestines” OR “horns” OR “horn” OR “feathers” OR “feather” OR “chicken heads” OR “chicken head” OR “chicken feet”))	2 580	1 862
3	Theme	(TITLE-ABS-KEY (“Slaughterhouse” OR “abattoir” OR “slaughterhouses” OR “abattoirs”) AND TITLE-ABS-KEY (“Abattoir waste” OR “livestock and slaughterhouse waste” OR “by-product” OR “by-products” OR “poultry waste” OR “red meat waste” OR “blood” OR “manure” OR “hides” OR “hide” OR “hooves” OR “trimmings” OR “trimming” OR “skin” OR “skins” OR “effluent” OR “effluents” OR “intestines” OR “horns” OR “horn” OR “feathers” OR “feather” OR “chicken heads” OR “chicken head” OR “chicken feet”) AND TITLE-ABS-KEY (“Resource recovery” OR “product recovery” OR “sustainable waste management” OR “disposal” OR “volarisation” OR “circular economy” OR “circular agriculture” OR “utilisation” OR “resource utilisation” OR “product utilisation” OR “value-added products” OR “value-added product” OR “value-added” OR “regeneration” OR “sustainable disposal”))	215	110

Search level 1 was used to extract only articles related to the slaughterhouses or abattoir industry and not any other type of industry or waste-generating facility.

Search level 2 focused more on the type of slaughterhouse derivatives generated by the slaughterhouse industry. For example, search terms such as “red meat waste“ and “poultry waste“ were used together with related red meat and poultry slaughterhouse derivatives such as “blood“, “hides“, “hooves“, “feathers“, “chicken heads“, and “chicken feet“ to limit the search to the specific search criteria.

Search level 3 was used to specify the analysis theme that should mainly focus on sustainable and circular topics, such as the recovery and use of the slaughterhouse derivatives in the previous search level, and common treatment technologies. This search level was also necessary to limit the search to focus specifically on the management, treatment, and disposal of slaughterhouse derivatives and not on the physical properties or any other characteristics of the slaughterhouse derivatives.

The search was embedded (level 2 was searched within the results of level 1; level 3 within levels 1 and 2). Thus, in the end, the number of scientific publications found on Scopus in search level 1 was reduced from 19 822 to 389. Likewise, the number of scientific publications on WOS declined from 14 446 to 165. During the search, quotation marks were used to search for specific terms. The keywords were looked for in document titles, abstracts, and keywords. All keywords were searched in Scopus and Web of Science

(WOS) as loose phrases. The bibliographic data for this research was gathered from both databases with no limitations on the search (such as topic area or document type) apart from the year of publication. Therefore, the investigation was conducted for the publication period of 2012 up to and including 2022 and was performed in April 2022.

2.2. Stage 2: Database selection

Scopus, a peered-reviewed literature search engine and database that includes abstracts and citations, together with WOS, which is a multidisciplinary database that indexes the most frequently cited journals in the respective fields, were used to retrieve publications for the state-of-research analysis [19] [21] [22]. In every publication in Scopus and WOS, many details of the scientific publications are included, such as the publication year, authors, addresses, title, abstract, journal, and references [20] [21]. These two databases allowed for a comprehensive coverage of the peer-reviewed scientific literature and high-citation records.

2.3. Stage 3: Data collection

Identifying and delineating a scientific network by scanning literature databases for keywords is difficult, since the outcomes depend a great deal on the keywords used. To address this, Figure 2 provides complete transparency about the decisions taken throughout the investigation and the selection of relevant documents.

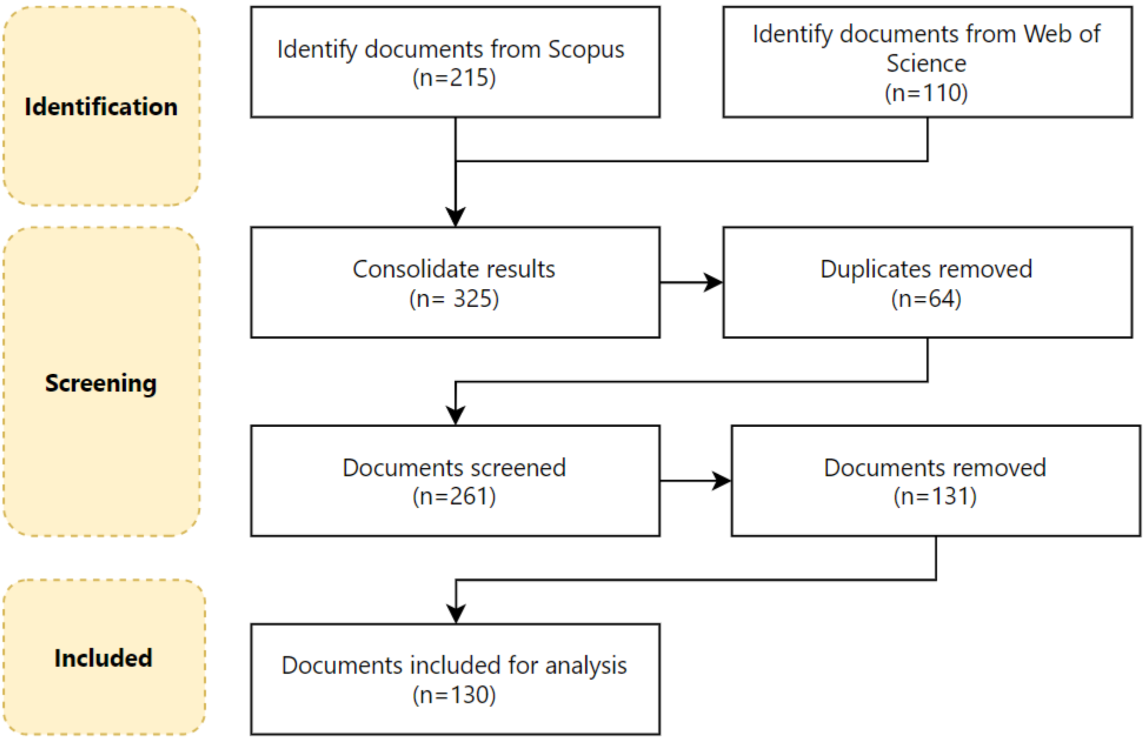

Figure 2: Document selection and evaluation procedure followed

First, to ensure the reliability of the retrieved data, multiple combinations of the topic keywords presented in Table A were used to retrieve the related documents.

A total of 215 documents on Scopus and 110 documents on WOS were collected for the period from 2012 to 2022 inclusive. After retrieving the documents under each combination of topic keywords from the two databases, all of the retrieved papers were fused to delete duplicate records. The documents were then screened by carefully reading them to identify whether each document's context was relevant to the scope of this study.

During the document selection, the following quality attributes were observed: the study objective, the slaughtering derivatives used in the study, the description of the types of experiment, and the results of the experiments conducted. After the screening process, 131 documents were removed to obtain the final retrieved documents – a total of 130 documents.

Once the data search had been finalised, the documents were exported with all the available information (including the title, author, abstract, keyword, and citation information) in the '.txt' format and in MS Excel format, which was used for the analysis.

2.4. Stage 4: Data analysis

As previously stated, bibliometrics is a valuable tool for analysing academic publications quantitatively [18]. Various bibliometric tools could have been used to analyse the data quantitatively that was collected through the keywords used in Table A. In addition, bibliometric software tools such as CiteSpace, VOS-viewer, Bibliometrixs, and many others could have been used to display graphically and to analyse the statistical findings on the academic texts that were retrieved [18].

In this study, VOS-viewer version 1.6.18 was used for the literature analysis.

VOS-viewer is a free program that analyses scientific publications imported from preferred databases such as Scopus and WOS. VOS-viewer visualises the associations between keywords, authors, and countries by producing two-dimensional maps based on the bibliographic coupling, co-authorship, citation, co-citation, and co-occurrence of keywords, authors, and countries [21] [23]. The program also allows for data extraction to MS Excel for further analysis.

Each two-dimensional network consisted of items (circles) with links between the items. The term 'VOS-viewer' stands for 'visualisation of similarities'. The approach used by the program is distance-based. Therefore, the items (circles) in a bibliometric network are positioned so that the distance (link) between two items indicates their relatedness. The smaller the distance between two items, the higher their relatedness. A cluster is a set of items included in a map. Clusters contain items that are closely related, together with the links between them. The clusters are different colours, making it possible to differentiate between them.

2.5. Stage 5: Presentation of results

The results of the data processing and analysis and a quantitative evaluation of the examined phenomena are presented in the sections that follow. Detailed results and visualisations are provided, and a discussion and conclusions section follows them.

3. BIBLIOMETRIC ANALYSIS

This section contains the results obtained from analysing the retrieved publications using VOS-viewer and MS Excel. The analysis includes the number of annual publications, most often cited publications, and countries, including a keyword analysis and the identification of treatment technologies.

3.1. Annual publications and growth trends

To answer RQ1, the output of annual publications was measured. When researching a specific field of interest, it is essential to evaluate the research area or topic by considering the number of scientific papers published during a particular period. The number of scientific documents related to the search terms specified in Table A increased over the analysed period, as shown in Figure 3.

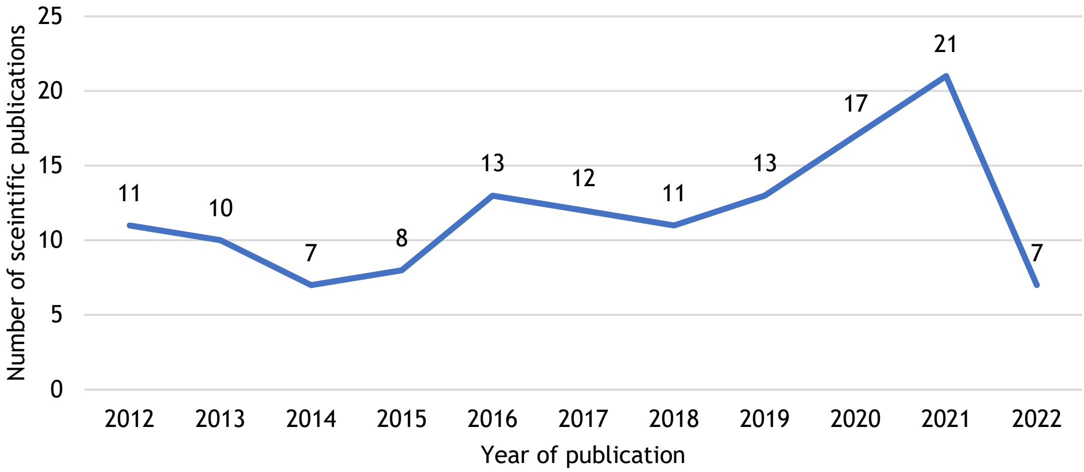

Figure 3: Number of scientific documents published annually from 2012 to 2022

A total of 130 relevant scientific papers was found to be published over the years 2012–2022. The number of publications decreased slightly from 2012 to 2014. The slight decline of papers in 2014 and in 2018 could have been because the concept of a circular economy – and therefore the adoption of a circular economy by the slaughterhouse industry – has only gained increasing attention over the past five years from scholars, practitioners, global companies, and politicians for its theoretical conceptualisation and its practical implementation strategies [24], [13], [25], [11]. The decrease in papers in 2022 occurred because this research was conducted at the beginning of 2022; thus, more publications could be expected for 2022, potentially totalling more than those in 2021.

3.2. The most often cited publications

The most often cited and most influential publications (n = 15) on the management of slaughterhouse derivatives are presented in Table A.1 in Appendix A. In Table A.1, specific information on frequently cited publications is given, including the author, source type, year of publication (Y), and the number of citations (C).

Most of the publications with a high number of citations were published between 2012 and 2016. These publications mainly focused on anaerobic digestion to treat slaughterhouse derivatives, specifically slaughterhouse wastewater, to produce biogas.

It is important to emphasise that, in general, the more citations a publication has, the more significant the impact, reputation, and quality of the publication [26]. However, that is not always the case, since some authors tend to argue that the number of times a publication has been cited does not always reflect its quality, but rather the publication's visibility [26], [27].

Furthermore, the number of times a publication has been cited is strongly linked to the period during which the publication was published [28]. Therefore, although older publications tend to have been cited more, this does not rule out the possibility of recent publications having a significant impact in the particular research field or in the near future [29].

3.3. Bibliographic coupling of publications

The bibliographic coupling of documents analyses the connection or the link between different documents or scientific publications based on the number of references they share [30]. The more references two or more documents share, the stronger the link between the papers [30]. In Figure 4, the size of each circle represents the number of citations of a specific document. The distance between the circles represents the relatedness and the similarity between the documents, while the different colours represent different clusters [30].

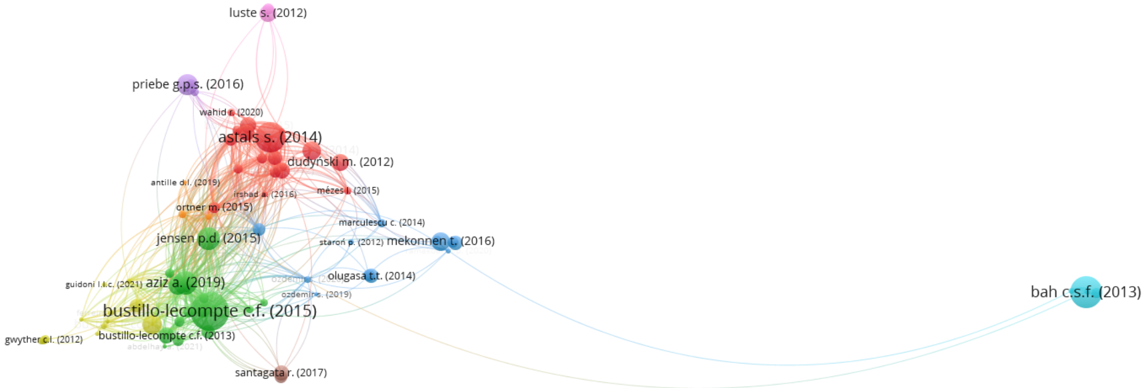

Figure 4: Bibliographic coupling of publications

Furthermore, the results obtained in Figure 4 show a threshold of four citations. In total, ten clusters can be identified from the visualisation. Three clusters are predominant in the figure: the blue cluster (on the right) with the author C.S.F. Bah and their citations (n= 142); the green cluster (at the bottom) with the author C.F. Bustillo-Lecompte and their citations (n = 51); and the red cluster (at the top) with the author S. Astals and their citations (n = 129). From Figure 4, the author C.S.F. Bah has a weak link with the rest of the publications. This means that the references used in that publication have nothing in common with the rest of the publications. However, this does not indicate that the publication does not influence the research field; so the author is still included in the research. The weak link between the author and the rest of the authors also might be a research gap, and might indicate a topic of interest on which researchers should focus more.

3.4. Analysis of countries

An analysis of countries is used to identify the most often referenced and most influential countries. The analysis determines the relationships between the countries, based on the number of times each country has been cited. The size of each circle represents the number of citations for that country. The circles' distances represent the connection and cooperation between countries, while the colours of the circles represent different clusters [30].

Figure 5: Analysis of the most often cited countries

Only the results meeting a threshold of one publication on the topic are shown. From Figure 5, four different clusters were identified: the cluster in blue (Canada, n = 373 citations), the cluster in red (Australia, n= 232 citations), the cluster in yellow (Spain, n= 218 citations), and the cluster in green (Brazil, n= 117 citations). These are the countries that were most often cited in publications.

The geographical distribution of the scientific literature reflects the extent to which slaughtering derivatives are viewed as a problem in various parts of the world. The visualisation shows that researchers from multiple countries are actively researching and identifying ways to recover the derivatives produced by slaughterhouse operations.

3.5. Co-citation analysis of authors

A co-citation analysis of authors studies the relationships or connections between authors, based on the number of times they are cited together. In the visualisation in Figure 6, the size of each circle represents the number of times an author has been cited. The circles' distances represent the relatedness, similarity, and cooperation between authors, while the different colours represent different clusters [30], [21].

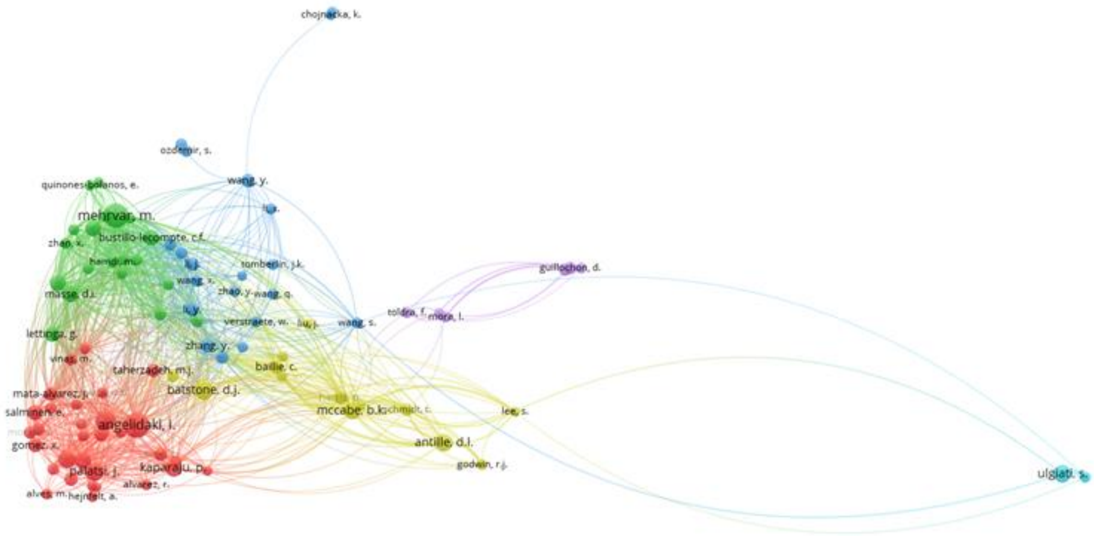

Figure 6: Co-citation analysis of authors

The results in Figure 6 shows a threshold of 12 citations. In total, six clusters could be identified from the visualisation. The scientific publications of authors in the red cluster (at the bottom left) focused on biomass and bioenergy. The publication of author I. Angelidaki (n= 71 citations) focuses on the anaerobic digestion of slaughterhouse by-products such as bones, fat, blood, and hair to produce biogas [31].

The green cluster (top left) includes authors who published papers related to environmental management. Author M. Mehvar (with n=69 citations) was cited most often in the green cluster. The publications of this author were all related to the disposal, treatment, and use of slaughterhouse wastewater through advanced biological and oxidation processes such as anaerobic digestion [32].

The dark blue cluster (top middle) includes authors whose publications related to renewable energy. Author Y. Zang (with n= 22 citations) published an article focusing on the co-digestion of the mechanically recovered organic fraction of municipal solid waste with slaughterhouse wastes. The article focused on mixing pig intestines and sheep blood with municipal solid waste to recover and use the waste [33].

The yellow-green cluster at the bottom right includes the scientific publications of authors in that cluster who focused on environmental and chemical engineering. Authors Antille *et al.* (with n= 35 citations) focused on the long-term land application of slaughterhouse cattle paunch effects on soil properties [34].

The purple cluster (top right) includes authors who published papers related to food chemistry. Author D. Guillochon (n=19 citations) published an article on harnessing slaughtering derivatives for high-value natural food preservatives [35].

The scientific publications of authors in the light blue cluster (on the right of Figure 6) focused on cleaner and more sustainable production through applied energy. Author S. Ulgiati (n=39 citations) published articles on the circular economy and electricity production from slaughtering derivatives [36].

3.6. Keywords

Aiming to answer RQ2, the keywords used in the scientific publications included in the study were analysed. The co-occurrence of authors' keywords was analysed (see Figure 7) to characterise their articles. The co-occurrence of authors' keywords is the number of scientific publications in which an author used specific keywords in relation to other scientific publications. The size of each circle represents the number of times a certain keyword was used: the bigger the circle, the higher the frequency of the keyword. The distances between the circles reflect their relationships: the shorter the distance between the circles, the stronger the correlation between them. The different colours represent different clusters. For the analysis, only the keywords that met the threshold of one citation are presented in Figure 7.

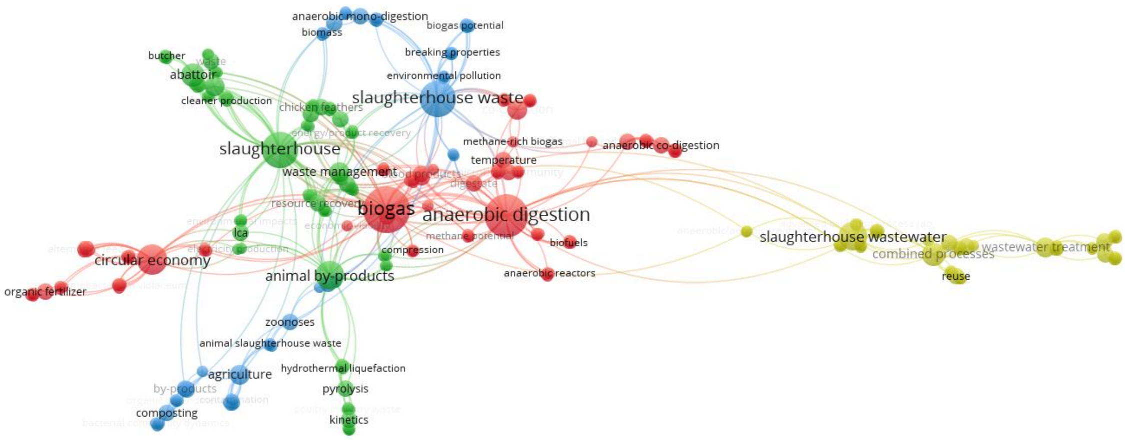

Figure 7: Co-occurrence of authors' keywords

The VOS-viewer's visualisation, shown in Figure 7, provides a quick overview of keyword co-occurrence, and links six clusters of co-occurring keywords. The visualisation of the keywords assisted in the process of identifying the most common type of treatment technologies used to dispose of slaughtering derivatives. First, from looking only at the figure, the keyword "biogas" had the highest occurrence. Likewise, "anaerobic digestion" (n= 61 citations); "slaughterhouse" (n= 50 citations); "slaughterhouse waste" (n= 42 citations); "circular economy" (n= 31 citations); "animal by-products" (n= 27 citations); "slaughterhouse wastewater" (n= 22 citations); "abattoir" (n= 20 citation); and "combined processes" (n=18 citations) were also keywords that most frequently occurred in the scientific publications.

The term "circular economy" had a total link strength of 31. The term was closely related to other keywords such as "animal feed", "insects", "bio-economy", "blowfly", and "organic fertilisers". The term also showed relatedness to other terms such as "animal by-products", "biogas", and "renewable energy".

The term "biogas" had a strong relationship with the keywords "anaerobic digestion" and "slaughterhouse wastewater". Other keywords that had a strong relationship with the term "biogas" were "blood products" and "animal manure". This shows that the circular economy mainly focuses on alternative feed, organic fertilisers, or renewable energy through anaerobic digestion, animal manure, blood, and slaughterhouse wastewater to produce biogas.

The overlay visualisation of the authors' keywords shown in Figure 8 analyses when the data or specific phrases were published. The colours symbolise different scores, which indicate the average publication year. All of the keywords in yellow are those that were more recently published, whereas the darker colours represent keywords that were published longer ago.

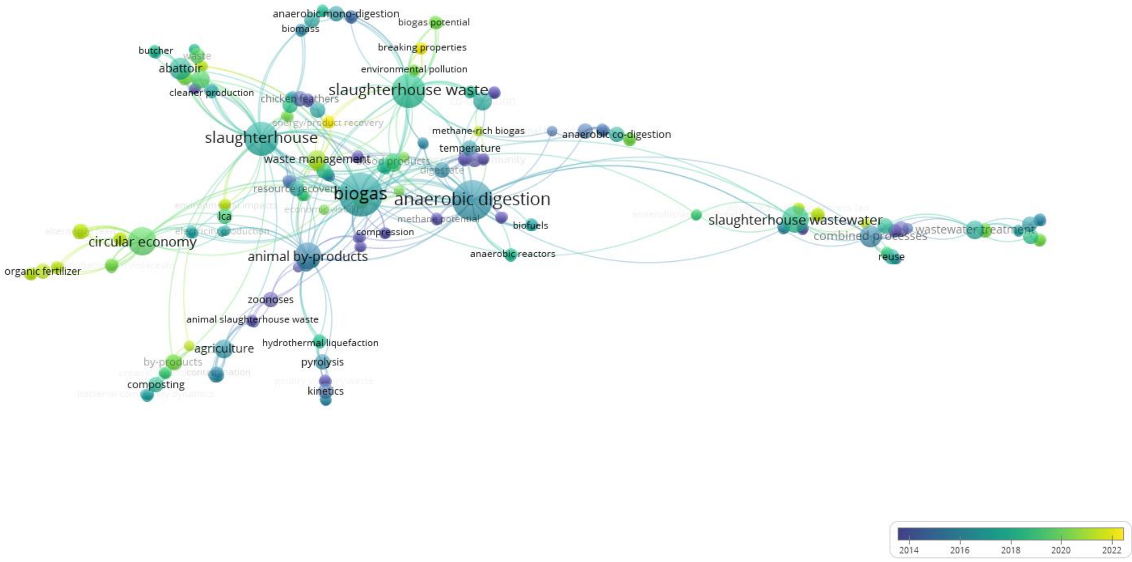

Figure 8: Overlay visualisation of the co-occurrence of authors' keywords

From Figure 8, terms such as "energy/product recovery", "breaking properties", "blowfly", "alternative feed", "organic fertilisers", "abattoir waste", "rendering condensate wastewater", and "high-rate anaerobic processes" were published more recently and so denote emerging themes. The keywords "anaerobic digestion" and "biogas" had been published quite a lot earlier than those terms, which explains why these two keywords also had a higher number of occurrences.

3.7. Identification of treatment technologies

To answer RQ 3, the scientific publications (n= 130) with potential relevance, as identified in Figure 2, were analysed. The publications were carefully scrutinised by carefully considering the following:

1. The objective of each study – to identify whether the study focused on the disposal of slaughterhouse derivatives and not on the pre-treatment of products before disposal.
2. The slaughtering derivatives used for the study – to identify the different derivatives and the types of animal that were slaughtered.
3. The descriptions and types of experiment that were conducted – to identify whether the experiments were only lab-scale experiments that focused on the characteristics of certain slaughterhouse derivatives, and whether the experiments focused more on the disposal of the products.
4. The results and conclusions of the experiments and the studies that were done – to identify whether the experiments were successful or unsuccessful in handling or disposing of the different slaughtering derivatives.

After thoroughly working through each of the scientific publications used for the bibliometric analysis, it emerged that the highest number of scientific publications related to biogas (anaerobic digestion – 53% of the publications). From the keyword analysis it was also evident that the production of biogas from slaughterhouse derivatives through the process of anaerobic digestion is an important area of research when it comes to the recovery of slaughtering derivatives, since the words "biogas", "anaerobic digestion", and "slaughterhouse" were the most prominent keywords in the literature that was analysed.

The rest of the publications focused on the recovery of slaughterhouse derivatives through rendering (13%) and composting (10%). The fewest publications were found to focus on novel treatment technologies, including pyrolysis (5%) and black soldier flies (1%), as shown in Figure 9.

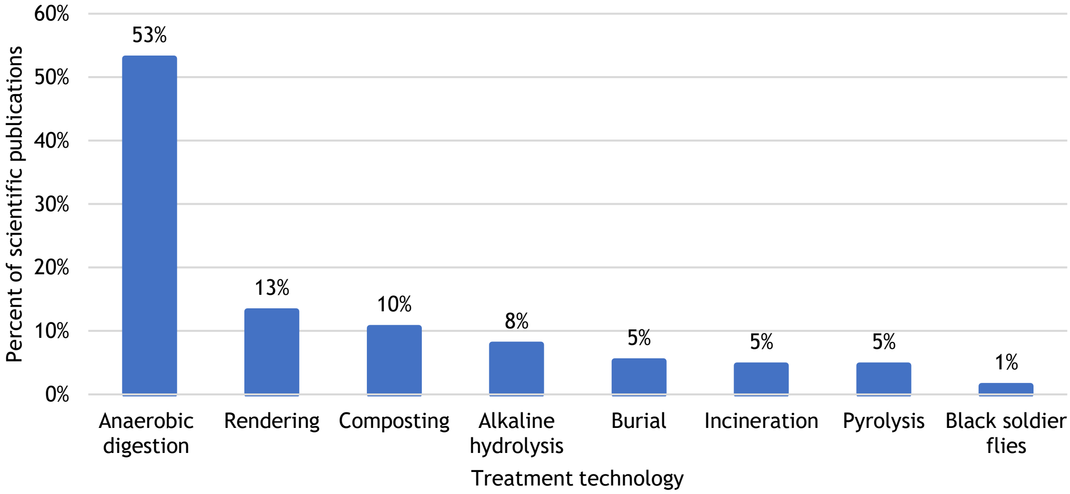

Figure 9: Total percentage of scientific publications in Scopus and Web of Science related to treatment technologies used for slaughterhouse derivatives (2012-2022)

Table A.2 summarises each technology in respect of the input and output materials generated by each method. Different input materials and output materials are required for each technology. Therefore, depending on the different slaughtering derivatives that were generated and the different slaughterhouses, a different type of technology could use the derivatives and so reproduce goods and services from them. It is essential to note that, from Table A.2, burial was the only technology that did not produce output materials that could be recovered and used. For this reason, burial was the only process among all the other processes identified in Figure 9 that could not be classified as a circular process.

4. DISCUSSION

The bibliometric analysis gave an overview of the scientific literature on treatment technologies for slaughtering derivatives published between 2012 and 2022. The research used 130 scientific publications from 399 authors and 45 countries. Over the past ten years, the amount of the literature on treatment technologies has followed an exponential curve (as shown in Figure 3), indicating an explosion in this specific field of research. The increase also suggests that there is a renewed interest in the sustainable recovery of slaughtering derivatives.

The results obtained from the bibliometric analysis revealed:

1. The most important and influential researchers in the field of research.
2. The most often cited publication (n= 206 citations in 2015) by authors C.F. Bustillo-Lecompte and M. Mehvrar, entitled "*Slaughterhouse wastewater characteristics, treatment, and management in the meat processing industry: A review on trends and advances*".
3. Spain as the country that was cited most often in documents related to the disposal of slaughterhouse derivatives.
4. Keywords such as “biogas” and “anaerobic digestion” as the most often cited keywords used by authors in this study.

The bibliometric analysis, looking at the most often cited publications, showed that most of the scientific publications focused on the treatment technologies for slaughterhouse wastewater/effluent. This indicated that the wastewater generated by slaughterhouse operations was the most crucial and problematic derivative on which researchers tended to focus.

As could be understood from the 130 identified scientific publications on treatment technologies, the recovery of slaughtering derivatives could contribute significantly to more sustainable and circular economical routes through the re-use of the products, especially as animal feed or soil fertilisers, or to produce biogas, as shown in Table A.2.

The recovery could be carried out through processes such as anaerobic digestion to produce biogas and digesters (organic soil for fertilisers), or through rendering to produce fats and other protein-rich meals, such as blood meal, bone meal, meat meal, and meat and bone meals that could be used for animal feed.

Other processes such as composting could be used to produce soil improvers and soil fertilisers and pyrolysis for the production of bio-oil, biochar, and syngas [3], [37], [38]. Gelatine, collagen, and other valuable materials could also be extracted from slaughterhouse derivatives, including the hides and skins of fallen or slaughtered animals [39], [40].

5. CONCLUSION

This article used a bibliometric analysis to identify the various treatment technologies or practices used to handle and dispose of specific slaughterhouse derivatives. A total of 130 scientific publications was analysed to determine the most often cited publications, the most often cited countries, the co-citation analysis of authors, the co-occurrence of authors' keywords, and the most common treatment technologies that could be used to dispose of slaughtering derivatives.

As revealed by the bibliometric analysis, several treatment technologies could be used to treat slaughterhouse derivatives. From the analysis it was evident that the amount of research on more sustainable treatment technologies for the disposal of slaughterhouse derivatives increased each year, with one treatment technology – anaerobic digestion – being the most researched and circular-economy-related process of them all.

The disposal and use of slaughtering derivatives is an important stage in the meat production continuum. The practical challenge is to minimise the adverse impacts of slaughtering derivatives and, if possible, to transform them into valuable products. This study has highlighted the importance of focusing on technologies that slaughterhouses could implement to optimise the use of resources over the entire production chain. Such increased efficiency is foreseen as part of a new paradigm for sustainable production and consumption in which lifestyles for resource optimisation are also an essential aspect of the expected environmental improvement to complement technological options for material recovery.

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6. APPENDIX A

Table A.1: The most often cited publications

Title	Author	Journal	Year/Citations
Slaughterhouse wastewater characteristics, treatment, and management in the meat processing industry: A review on trends and advances	C.F. Bustillo-Lecompte and M. Mehvrar	Journal of Environmental Management	2015/ 206
Slaughterhouse blood: An emerging source of bioactive compounds	C.S.F. Bah, A.E. Bekhit, A. Carne, and M.A. McConnell	Comprehensive Reviews in Food Science and Food Safety	2013/ 142
Identification of synergistic impacts during anaerobic co-digestion of organic wastes	S. Astals, D.J. Batstone, J. Mata-alvarez, and P.D. Jensen	Bioresource Technology	2014/ 129
Conversion of phenols during anaerobic digestion of organic solid waste – A review of important micro-organisms and impact of temperature	I. Leven, K. Nyberg, and A. Schunrer	Journal of Environmental Management	2012/ 80
Biological wastewater treatment (anaerobic-aerobic) technologies for safe discharge of treated slaughterhouse and meat processing wastewater	A. Aziz, F. Basheer, A. Sengar, Irfanullah, S.U. Kahn, and I.H. Farooqi	Science of The Total Environment	2019/ 76
Anaerobic membrane bioreactors enable high-rate treatment of slaughterhouse wastewater.	P.D. Jensen, S.D. Yap, A. Boyla-Gotla, J. Janoschka, M. Pidou, and D.J. Batstone	Biochemical Engineering Journal	2015/ 74
Anaerobic digestion of chrome-tanned leather waste for biogas production	G.P.S Priebe, E. Kipper, A.I. Gusmao, N.R. Marcilio, and M. Gutterres	Journal of Cleaner Production	2016/ 61

Table A.1: The most often cited publications (cont.)

Title	Author	Journal	Year/Citations
Treatment of an actual slaughterhouse wastewater by integration of biological and advanced oxidation processes: Modeling, optimization, and cost-effectiveness analysis	C.F. Bustillo-Lecompte and M. Mehvrar	Journal of Environmental Management	2016/ 51
Potential of anaerobic digestion for material recovery and energy production in waste biomass from a poultry slaughterhouse	Y.-M. Yoon, S.-H. Kim, S.-Y. Oh, and C.-H. Kim	Waste Management	2014/ 49
Valorization of rendering industry wastes and co-products for industrial chemicals, materials and energy: review	T. Mekonnen, P.Mussone, and D. Bressler	Critical Reviews in Biotechnology	2016/ 48
Treatment of slaughterhouse wastewater in a sequencing batch reactor: Performance evaluation and biodegradation kinetics	P. Kundu, A. Debsarkar, and S. Mukherjee	BioMed Research International	2013/47
From feathers to syngas – Technologies and devices	M. Dundynski, K. Kwiatkowski, and K. Bajer	Waste Management	2012/ 42
Co-digestion of dairy cattle slurry and industrial meat-processing by-products – Effect of ultrasound and hygienization pre-treatments	S. Luste, A. Debsarkar, and S. Mukherjee	Bioresource Technology	2012/ 39
Anaerobic co-digestion of sludge: addition of butcher's fat waste as a co-substrate for increasing biogas production	E.J. Martinez, C. Fernandez, J.G. Rosas, and X. Gomez	Plus One	2016/ 36
Methane potential of sterilized solid slaughterhouse wastes	P. Pitk, P. Kaparaju, and R. Vilu	Bioresource Technology	2012/ 36

Table A.2: Overview of treatment technologies

Treatment technology	Input materials	Output materials	End-uses	Key references
Anaerobic digestion	Animal manure, sewage sludge, blood, meat, bones, cattle rumen	Carbon dioxide, biomethane gas, nutrient-rich digestate	Heat production, electricity production, organic soil fertilisers	[19], [41], [42], [43], [44], [45], [46]
Rendering	Animal hides and skins, bones, hair, fats, blood, manure	Pelleted soil additives, meat and bone meal (MBM), meat meal, bone meal, blood meal, feather meal, tallow (fats and oils), and specific risk materials (SRM).	Animal feed, soap, candles, biofuels (biodiesel and biogas), grease	[47], [48], [49], [50], [51], [48], [7], [52], [39]

Table A.2: Overview of treatment technologies (cont.)

Treatment technology	Input materials	Output materials	End-uses	Key references
Composting	Hides and skin, bones, hooves and horns, meat trimmings, sewage sludge, blood, inedible offal, tissues, animal manure, stomach and intestines, animal hair, feathers, other decomposable organic materials and bulking agents	Organic matter (including carbon, chemical energy, nitrogen, protein, humus), minerals, water, and micro-organisms	Organic soil fertiliser	[53], [54], [55], [56], [57], [3], [19], [37], [58]
Alkaline hydrolysis	Animal carcasses and other infectious materials	A sterile aqueous solution (consists of tiny peptides, amino acids, sugars, and soaps)	Organic fertiliser, C and N soil supplement, or feedstock	[59], [52], [60], [61]
Burial	Any slaughterhouse waste	N/A	N/A	[59], [7]
Incineration	Hides and skin, bones, feathers, poultry manure, meat and bone meal, cattle manure, and sewage sludge	Heat (steam) and ash (slag)	Electricity, heat, high-value-added fertiliser	[40], [63], [3], [64], [65]
Pyrolysis	Sewage sludge, animal manure, chicken heads and feet, intestines, meat residues, offal, hides and skin, feathers	Gas, liquid (biofuel), solid (biochar)	Biochar: Solid fuel, animal feed, soil amendment, production of catalyst and contaminant absorbents. Bio-oil: Electricity and heat production in biofuels, furnaces, combustors, diesel engines and gas turbines. Gas: Heat, electricity	[19], [66], [67], [68], [69], [70], [71], [38], [3], [72]
Black soldier flies	Animal manure, sewage sludge, agricultural and crop residues, food waste, organic fraction of municipal solid waste	Dead adult flies, insect meal/cake, fats and oils, residue	Organic soil fertiliser, pigments, bioplastics, protein hydrolysate, edible film, binders, chitosan, biodiesel, lubricant agents, or animal feed	[73], [49], [74], [75], [76], [77], [78], [79], [2], [80]