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Systematic Review

Opportunities for Waste to Energy in the Milk Production Industry: Perspectives for the Circular Economy

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Abstract: Cheese whey is a waste produced in the dairy industry which generates problems if it is dumped directly into the sewer due to its high organic load. An alternative for cheese whey management is anaerobic digestion, a biological process that transforms organic matter into biogas and digestate, two products with significant energy and agricultural potential. This work was aimed at contributing to the building of knowledge about the anaerobic degradation of cheese whey, developing a bibliometric analysis, and tracing trends in related research from 2010 up to the present, using PRISMA® to develop a systematic review based on Scopus® and using Excel® and bibliometric software (VosViewer® and RefViz®) for the identification of information. Our results show that the research around cheese whey is relatively recent and that the highest percentage of publications is from 2018 onwards. Twelve variables of the anaerobic cheese whey degradation process were identified and grouped into five factors: substrate, reactor configuration, digestate analysis, microbiological analysis, and inoculum. Likewise, it was identified that most of the anaerobic processes allow the implementation of the circular economy into the dairy sector. In conclusion, the application of anaerobic digestion in the dairy sector can help to close the productive cycles, produce biofuels, and reduce pollution.

Keywords: biofuels; bioenergy; circular economy; anaerobic digestion; anaerobic co-digestion; cheese whey; digestate

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1. Introduction

According to the Food and Agricultural Organization [1], 8.01 $\times$ 10^8 t/year of milk is produced in the world, of which 37% is used to obtain cheese and other products, 30% is used for butter production, and the rest (33%) is used to produce yogurts and chocolate milks, among others. In addition, according to estimates by this same entity, the increase in production is about 10% every four years [1]. Worldwide, the largest milk producers are the USA and the European Union [2]. Thus, according to figures from Eurostat [3], in 2017 the European Union produced 1.7 $\times$ 10^8 t of milk, of which 93% was used to obtain dairy products (38% in cheese, 30% in butter, 12% cream, 11% fresh milk, 4% acidified milk, and 3% milk powder). For its part, the USA produced around 9.9 $\times$ 10^7 t of milk in 2019, which was mainly transformed into more than 600 types of cheese and milk powder [4]. In South America, meanwhile, milk production in 2018 was around 6.4 $\times$ 10^7 t/year, and production is expected to grow in countries such as Argentina, Colombia, Chile, and Uruguay [5].

Two main by-products are obtained from the dairy industry: effluents, including washing and pasteurization water, and cheese whey (CW) [6]. The former are mixed with detergents, and generally have low organic loads: 2.5 L of effluent per 1 kg of processed milk [3]. In contrast, CW is highly polluting as between 9 to 10 L of CW are obtained per 1 kg of cheese. Currently, around 50% of the dairy effluents in the world are discharged into the environment without any control [7]. This situation not only induces eutrophication in water bodies, but also increases the costs of water purification in treatment plants.

CW is composed mainly of lactose, proteins, and minerals (70–72%, 8–10%, and 12–15%, respectively, on a dry matter basis). Its pH ranges between 3.3 and 9.0; it contains between 0.01 to 1.7 g/L of Total Kjeldahl Nitrogen (NTK); its Chemical Oxygen Demand (COD) is in the range of 50–102 g/L; and its Biological Oxygen Demand (BOD) ranges between 27–60 g/L [8,9]. For these characteristics, CW is considered an attractive substrate for biological treatment through anaerobic digestion (AD), leading to bioenergy and biochemicals production [10,11]. AD is a multistage process of the transformation of organic matter (liquid or solid) that takes place in the absence of molecular oxygen and from which two main by-products are obtained: (i) biogas with high energy potential (composed mainly of methane CH_4) and (ii) digestate or biol that has amendment characteristics and can be used to improve soil quality. However, some studies have found that CW can also be used to obtain baby food, baked goods, vaccines, medications, shampoos, and toothpastes, among other products [12]. Likewise, it has been shown that CW can be recovered through AD [13–16].

Energy is a required element in many daily activities, such as transportation, cooking, and the production of heat and electricity for industrial processes. Around 80% of the energy used worldwide is obtained from fossil fuels [17], a controversial topic given the related greenhouse gas (GHG) emissions. Furthermore, the use of fossil fuels together with industrial processes generates 65% of global GHG emissions [18]. To attenuate this problem and contribute to the achievement of the Sustainable Development Goals (SDGs) [19], in particular the goals 2, 7, 12, 13, and 15, which seek to promote sustainable agriculture, guarantee affordable energy, combat climate change, and fight desertification, several countries, mainly European countries [20], have adopted the use of alternative energies such as AD.

It is important to mention that the implementation of many of these alternatives is a consequence of the transition that is being carried out by many companies nowadays from the traditional linear economy model (take–make-use–dispose) to the new paradigm of the circular economy (CE), which proposes the reincorporation of biological and technical waste into production chains [21]. Likewise, it is worth highlighting that despite there already being some methodological proposals in the literature [22–24] for making this transition, there is not yet a consensus about this topic.

Authors such as Kimming et al. [25], Dolman et al. [26], and Stanchev et al. [27] have found that although dairy sector wastes are drivers of different environmental impacts, they also offer advantages when they are reintroduced to processes. Indeed, CW and cow manure (CM) can be used as raw materials to obtain energy for the production processes in this sector. In Latin America, particularly in Colombia, some studies [14,28] have analyzed the biogas production potential at a laboratory scale and the production of struvite from CW. Nevertheless, it is still a subject of recent research.

To contribute to this body of knowledge about the anaerobic degradation of CW, this study aimed to (i) identify the research trends around this topic, (ii) establish the current research gaps, and (iii) analyze the contribution of CE to the use of CW. To achieve these goals, we started with a bibliometric analysis using google docs®, VosViewer®, and Refviz® that allowed us to know the geographical and temporal distribution of the academic production; to analyze author and word co-occurrence; to identify the top journals and main articles; and to create some clusters based on keywords. Worth mentioning is that this type of analysis allows the finding of research gaps and emerging fields of study. Likewise, it is useful to identify, for example, the most relevant countries, authors, and journals of a specific subject [29,30]. Then, we identified research trends around the degradation of cheese whey based on a content analysis of the documents used for the bibliometric analysis. This type of analysis allows the obtaining of a better understanding of a theme [31]. The

PRISMA® methodology was used to carry out the systematic review that allowed us to identify the literature to include in the analysis.

This article is organized as follows. Section 2 describes the methodology used. Then, in Section 3 (results) we present (Section 3.1) a spatial and temporal distribution of the scientific production around the anaerobic degradation of the CW and the authors and word co-occurrence map based on the bibliometric analysis. Then, in Section 3.2 we show the main research trends around the topic of interest. Lastly, Section 3.3 shows the main findings on circular economy in the biological utilization of AD/anaerobic co-digestion (A-COD) of CW from the perspective of the CE (Section 3.3). Section 4 presents a critical reflection upon the main findings. In Section 5, the conclusions are presented. Finally, we include an appendix with a glossary of the paper´s abbreviations.

2. Materials and Methods

2.1. Search Strategy

To identify the recent literature on CW anaerobic degradation, a systematic review process was carried out, following the methodology of PRISMA®. This methodology has been used in other studies, such as that of York et al. [32] and Mancebo et al. [33] in the identification of literature by the search for policy trends regarding the reduction of GHG derived from the dairy sector and the identification of waste-to-energy technologies, respectively. Figure 1 shows the stages followed to search and systematize the information. The observation window corresponds to the period from 2010 to the present.

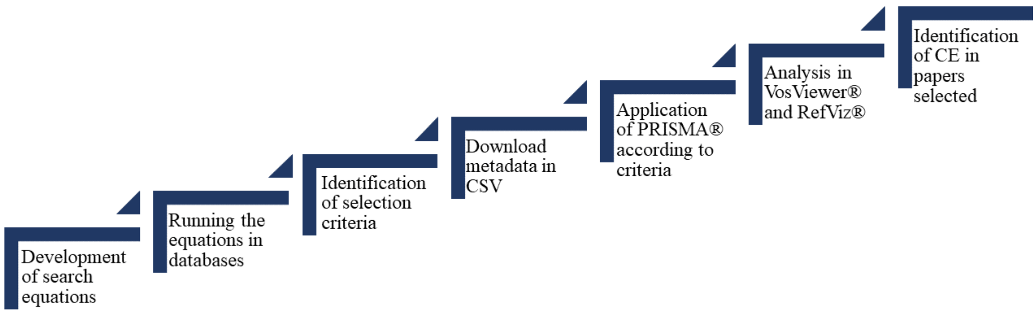

Figure 1. Stages of systematic review.

The search was developed in Scopus® on 1 September 2021. This database was used because it is considered one of the largest databases of peer-reviewed literature, widely recognized by the scientific community. The search equations were constructed with the keywords: anaerobic digestion, cheese whey, anaerobic co-digestion, methane, inoculum, stages, pretreatment, circular economy, digestate, and climate change, using the Boolean operators AND OR (see Table 1).

Table 1. Search equations.

ID	Equation
A	"Anaerobic digestion" AND "Cheese whey" AND Methane
B	"Anaerobic digestion" AND "Cheese whey" AND Inoculum OR Inoculum
C	"Anaerobic digestion" AND "Cheese whey" AND Stages
D	"Anaerobic digestion" AND "Cheese whey" AND "Anaerobic Co-digestion" OR "Anaerobic codigestion"
E	"Anaerobic digestion" AND "Cheese whey" AND Pretreatment
F	"Anaerobic digestion" AND "Cheese whey" AND Digestate
G	"Anaerobic digestion" AND "Cheese whey" AND "Climate change"
H	"Cheese whey" AND "Anaerobic co-digestion" OR "Anaerobic codigestion" AND Methane
I	"Anaerobic digestion" AND "Cheese whey" AND "Circular economy"

Once the equations were executed in Scopus®, the results were downloaded in CSV format and uploaded to the Excel® software. Then, the information was organized applying the PRISMA® methodology, taking into account the following criteria: (i) selection of research and review articles; (ii) title review; (iii) abstract review (items ii and iii were reviewed considering the presence of the words cheese whey and anaerobic co-digestion); and (iv) content of the article, that is, information on the CW, AD, or A-COD of beef cattle. This criterion was adapted from the review developed by Reyes-Torres et al. [34]. Finally, after applying these criteria, a total of 52 articles addressing the topic of the anaerobic degradation of CW were obtained (see Figure 2).

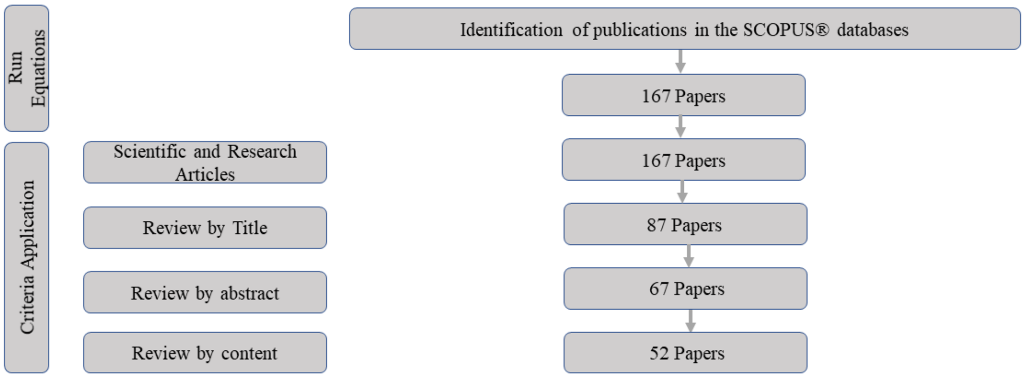

Figure 2. Flow chart for the selection of articles according to the PRISMA® methodology.

2.2. Information Synthesis and Analysis

To make a bibliometric analysis, the metadata obtained were taken and uploaded to Google docs® to analyze the temporal and geographical distribution of the research that has been developed worldwide in recent years on CW anaerobic degradation. The analysis led to the making of two graphs. The first corresponds to a world map where the main countries researching on CW anaerobic digestion are identified, and the second graph is a temporal bar graph, where the percentage of publications made from 2010 to 2021 about the AD/A-COD of CW is presented. Subsequently, for the identification of the authors and word co-occurrence and the identification of clusters, VosViewer® and Refviz® software in their free-version formats were used. These software programs have shown their usefulness in previous research on waste management in the framework of the CE [35], the composting of bio-waste [36], and the AD of food waste [37] using surveillance technology.

It should be noted that VosViewer® is a very useful tool in this type of study, not only because it allows the building and visualization of bibliometric networks through particular figures, but also because it establishes associations among authors and keywords. The distance between terms in the figure determines the strength of correlation between them, which is calculated through the proximity index or affinity index [38]. For the case presented in this paper, the authors must be repeated at least three times and keywords had to be repeated five times. Once identified, they were refined to avoid synonyms. RefViz®, for its part, helps to eliminate possible duplications in the information and groups the selected terms in clusters according to the information found in the database and its proximity. Thus, each cluster groups the articles that represent the similarity between their keywords. After clustering with Refviz®, we proceeded to review each article to identify research trends around the degradation of CW and the advances in the inclusion of the CE in the use of AD/ACOD of CW to identify research opportunities.

3. Results and Analysis

3.1. Bibliometric Analysis

In this section, we present the geographical location and the evolution over time of the production of articles related to CW anaerobic degradation. Then, we present the analysis of the authors and word co-occurrence, the top journals, the main articles, and the cluster identification, made with VosViewer® and RefViz®. Finally, we show the advances of the inclusion of CE in the biological use by AD/A-COD of CW.

3.1.1. Geographical Location of the Studies and its Evolution over Time

In general, AD has become very important in recent years because this technology allows the disposal of different organic waste streams and the production of two relevant by-products (biogas and digestate) with the corresponding energy and agricultural value. The geographical distribution of studies related to this technology applied to the CW is presented in Figure 3, where a greater intensity of the color indicates a greater percentage of articles associated with the country. It shows that Europe (57.5%) is the leader and that countries such as Italy and Greece are the main ones, followed by America (24.6%), where Brazil and Mexico stand out. For their part, in Asia (14.3 %), South Korea and China lead, while Australia and New Zealand excel in Oceania (3.6%); finally, no results were found for Africa.

Figure 3. Geographical distribution of the intellectual production on AD/A-COD of CW. Note: a greater color intensity indicates more intellectual production about anaerobic degradation of CW.

In LA (i.e., Brazil, Colombia, and Mexico), the anaerobic degradation has had a greater application for the treatment of wastewater [39] and solid waste, such as manure from cattle or pigs, derived from the breeding and raising of animals. Waste treatment has been mainly implemented through dome-type and tubular digesters, primarily due to their low costs of investment and operation, characteristics that make them more attractive for contexts where economic resources are limited [40].

Regarding research that has been developed about the use of CW and its connections to the principles of the CE, it was found that only eight articles have been published during the period under consideration [9,16,41–43]. Of these publications, seven are from Europe (Spain, Greece, Ireland, Italy, Portugal, the United Kingdom, and the Czech Republic) and one from Oceania (Australia). This might be explained by the fact that Europe has a higher level of development in CE applications than other continents [44], and therefore, they have already begun to migrate towards this new economic model, given its advantages, over the traditional linear model.

About the evolution that research on CW has had over time, it was found that 54.4% of the 52 identified articles were published during the 2018-to-2021 period, while 45.6% were released between 2010 and 2017 (see Figure 3). This shows that CW research is an emerging field of study which is becoming increasingly relevant given the growing need for the proper management of dairy effluents. According to the FAO, the dairy industry will see increases in annual cheese consumption of around 0.9% in developed countries and 0.8% in developing countries in the next 10 years [1].

The behavior observed in Figure 4 is similar to that shown by Casallas-Ojeda et al. [45] and Zamri et al. [46] for food wastes. This indicates an increasing interest in studies on AD, possibly associated with the relevance of this technological process in the treatment of wastes. It also agrees with the increase in the number of publications found by Lin et al. [47], who made a review on AD and composting with different substrates of organic origin (i.e., food waste, animal manure, and sewage sludge). These findings are probably related to the transition from the linear to the CE model that is gaining ground in countries, especially in Europe, in order to comply with the SDGs. Additionally, in the European countries, there are numerous incentives for research on AD, which explains why in Europe there are full-scale AD plants already in place [20].

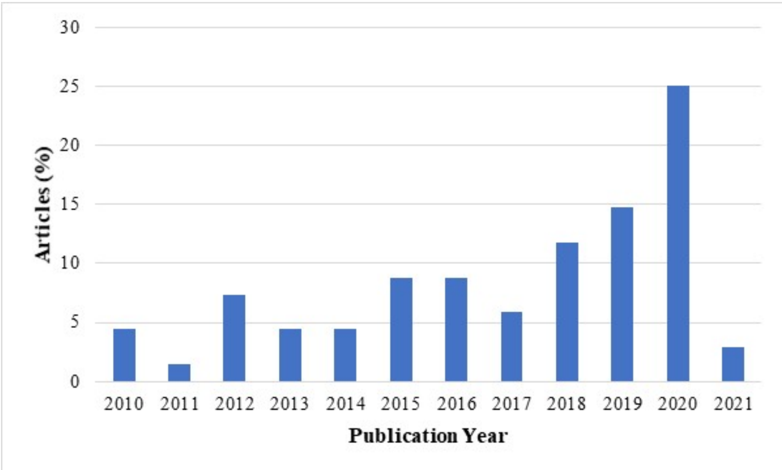

Figure 4. Temporal distribution percentage of articles published per year (2010–2021). Note: data for 2021 include articles until September.

Studies related to CW anaerobic degradation, from the perspective of the CE, appeared for the first time in 2017 [41]. However, it was only in 2020 when the largest number of publications appeared [9,16,42,43,48]. This finding allows the inference that the subject has not been extensively studied, which represents an opportunity for research in the context of Latin America and especially in countries such as Colombia, with a long tradition of dairy industries.

3.1.2. Author and Word Co-Occurrence, Top Journals, Main Articles, and Cluster Identification

Figure 5 shows the co-authorship network (co-occurrence) of the most productive authors based on the total number of published articles. It is observed that the authors Rodrigues J.A.D., Ratusznei, S.M., Lovato, G., and Albanez, R. are the ones who have published the most about CW AD/ACOD. This was corroborated through a review of each of the authors involved in the 52 publications found. For each of the authors, respectively, five, five, four, and three publications were found.

On the other hand, the 11 journals that have 57.7% (30 articles) of the publications are: (i) *Bioresource Technology* (11.5); (ii) *Waste Management* (7.7); (iii) *Applied Biochemistry and Biotechnology* (5.8); (iv) *Journal of Environmental Management* (5.8); (v) *Biochemical Engineering Journal* (3.8); (vi) *Biomass and Bioenergy* (3.8); (vii) *Energies* (3.8); (viii) *Journal of Chemical Technology and Biotechnology* (3.8); (ix) *Renewable Energy* (3.8); (x) *Science of the Total Environment* (3.8); and (xi) *Waste and Biomass Valorization* (3.8). The above mentioned authors have published in journals such as iii and v.

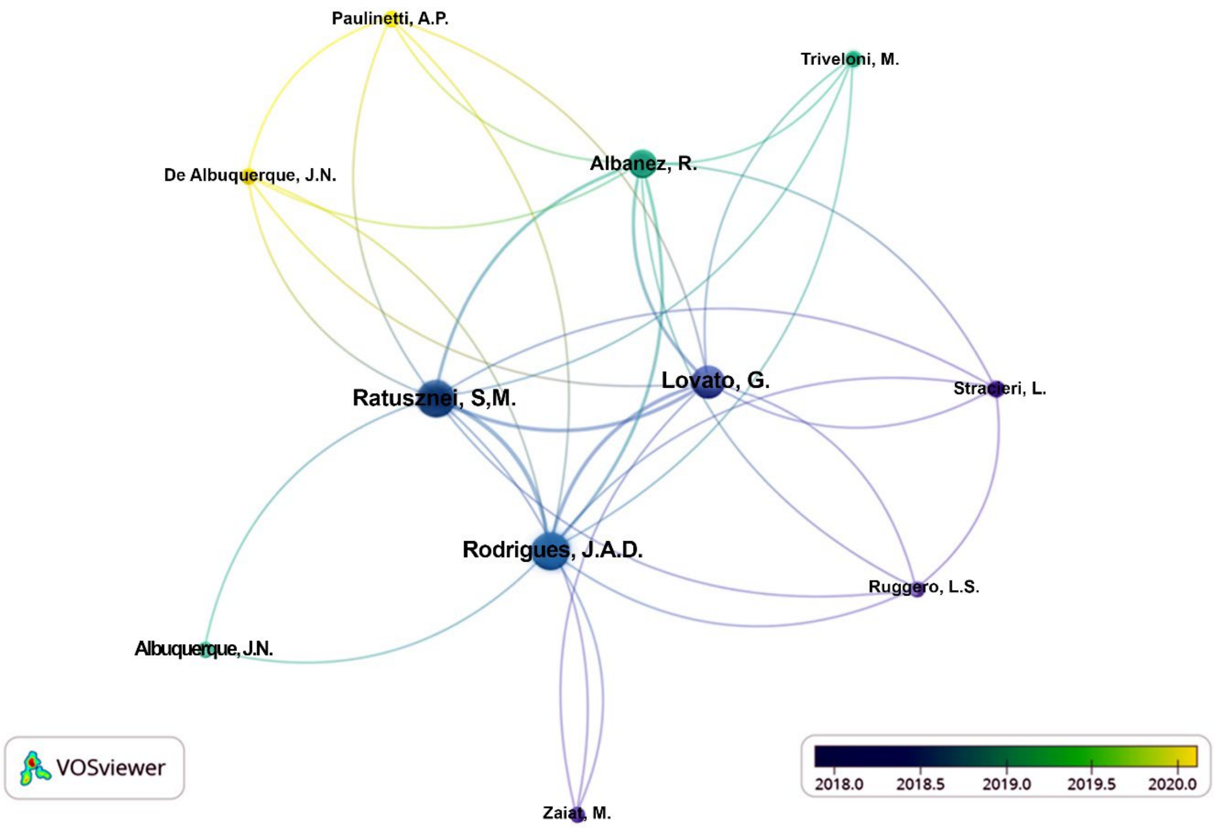

Figure 5. Co-authorship network (co-occurrence) of the most productive authors based on the total number of published articles. Note: the bubble size refers to the total number of the most productive authors, while line thickness and colour refer to link strength and clustering, respectively.

The most cited article (69 citations) was developed by Dareioti and Kornaros [49] in the journal *Bioresource Technology*, followed by that of Chatzipaschali and Stamatis [6], published in *Energies* with 66 citations. On the subject of CE the most cited article is by Dolman et al. [26], published in the *Journal of Cleaner Production*, with 41 citations.

Likewise, it was found that in the last two years two articles were the most cited: Microbial profiling during anaerobic digestion of cheese whey in reactors operated at different conditions, with 29 citations [50], and Enzymatic pretreatment to enhance anaerobic bioconversion of high strength wastewater to biogas: A review, with 25 citations [51], published in *Bioresource Technology* and *Science of the Total Environment*, respectively. It should be noted that these two journals contain the largest number of articles on this topic.

Figure 6 displays the co-occurrence map developed with the keywords of the 52 resulting articles after debugging. Three words stand out there: co-digestion, cheese whey, and anaerobic digestion, where the word cheese whey is the main connector between them. Likewise, there is evidence of a greater relationship between CW and A-COD because many studies about this residue have been focused on the mixture of substrates rather than on the mono-digestion of CW [52,53]. Among the wastes that have been mixed with CW, agro-industrial by-products, such as wastewater, bovine manure, and food residues are frequently mentioned [54,55].

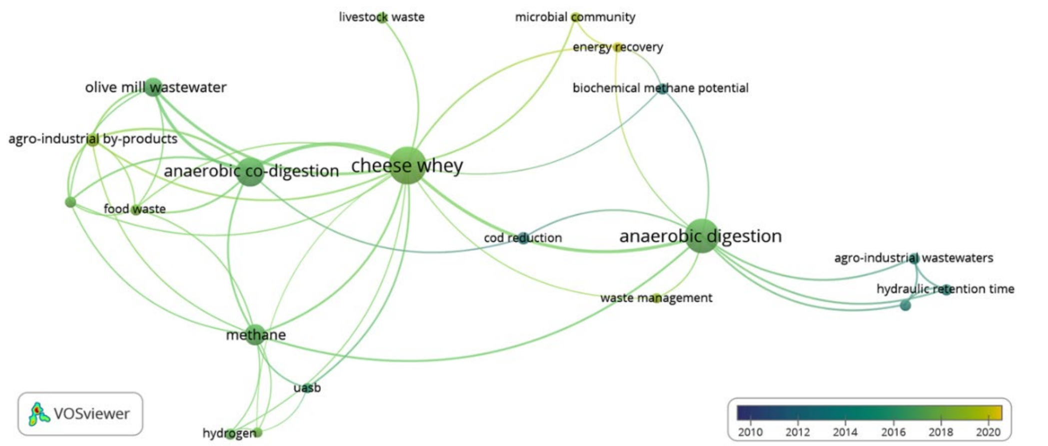

Figure 6. Keyword co-occurrence around anaerobic digestion/anaerobic co-digestion of cheese whey. Note: The bubble size refers to the total number of highly used keywords, while line thickness and color refer to link strength and clustering, respectively.

Likewise, Figure 6 shows that a common point between both types of degradation (AD and A-COD) is the reduction of organic matter in terms of chemical oxygen demand (COD reduction), and that their main purpose has been to obtain energy in the form of methane [56–58]. Hydrogen has also been studied but to a lesser extent [59]. Regarding the mono-digestion or AD of CW [60], tests were mainly performed through the biochemical potential methane method. In addition, operational conditions such as hydraulic retention time (HRT) have been evaluated. Surprisingly, there is no indication about the study of the digestate or the scale of the reactor within this co-occurrence of words. Therefore, it can be deduced that there are still research gaps in these topics.

Figure 7 shows 12 clusters (G1 to G12) resulting from grouping keywords according to their similarity. In general, it was found that the keywords are grouped into factors (clusters) such as those reported by authors such as Casallas-Ojeda et al. [45] and Cárdenas-Cleves et al. [61]. Indeed, the clusters' substrate and environmental factors, inoculum, and experimental configuration coincide with these studies. However, in this work, two new clusters were identified: digestate and microbiological analysis. The substrate was the factor with the highest number of associated publications (27), followed by reactor configuration (19), digestate analysis (4), microbiological analysis (2), and the inoculum (1).

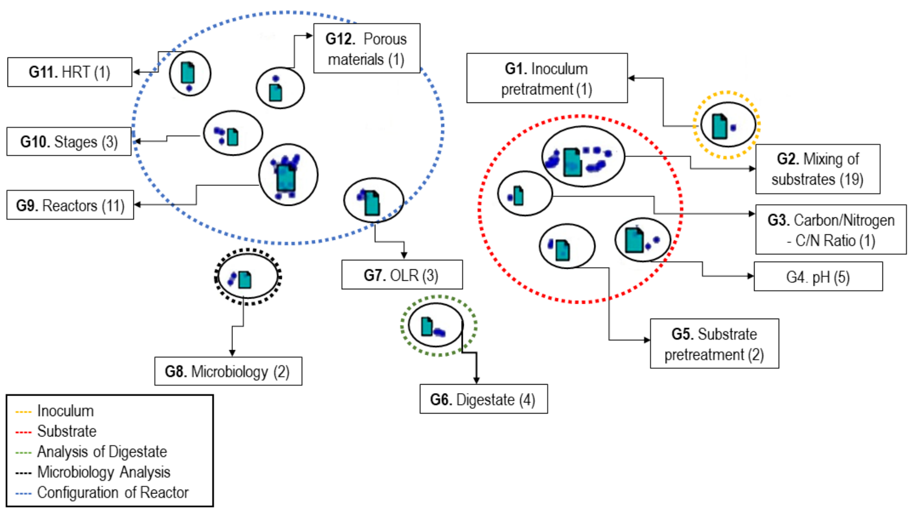

Figure 7. Research trends about AD/A-COD of CW. Note: C/N Ratio: Carbon/nitrogen ratio; OLR: Organic load rate; HRT: Hydraulic retention time. The values in parentheses indicate the number of publications in each cluster.

Unexpectedly, the circular economy does not appear in Figure 6. It is probably because this concept has not yet been widely used in conjunction with AD/A-COD. Hence, it is not included in the articles' keywords, and therefore, it is not reflected in the co-occurrence analysis. This suggests that the inclusion of CE principles in the dairy sector represents a valuable research opportunity.

It is remarkable that in the co-occurrence of words (Figure 6) there was no evidence of any relationship with the term digestate, but when clustering using RefViz® (Figure 7), four articles were found that addressed this by-product of anaerobic degradation. This contradiction might be because the keyword (digestate) is not repeated enough times to be included in the analysis. Likewise, even when the term hydraulic retention time was identified in the co-occurrence of words, only one publication was found in this regard. Provided that only 13.7% of the total articles (52) study different variables simultaneously, it is possible that in the low number of articles this interfered and categorized them in another cluster. It is important to note that the study of variables simultaneously can show interaction phenomena that are not visible when the variables are evaluated independently [62]. Thus, analyzing the variables in a multivariate way using, for example, response surface analysis, implies a decrease in the experimental time and the number of treatments as the same experimental unit is used with the combination of more than one variable [63].

3.2. Research Trends around the Degradation of Cheese Whey

In this section, the five factors identified with RefViz® (Figure 7) are presented and the main findings of each variable that make up the different factors are described. Additionally, trends and information gaps were identified.

3.2.1. Trends Associated with the Inoculum

Some of the inoculum characteristics, such as being granular or flocculent, determine the biogas production. It should be noted that the granules have greater microbial activity, which stimulates the substrate degradation, obtaining higher biogas productions [64]. In general, most AD studies refer to the sludge from wastewater treatment plants (WWTP), given its wide availability, although inoculum from agro-industrial waste treatment plants, chicken excrement digesters, and cattle or pig farms is also reported [65]. The choice of the inoculum source depends, among other aspects, on the accessibility, availability, and affinity that it may have concerning the residue to be digested. According to this, the duration of the acclimatization period, better known as the lag phase, is defined.

There are some strategies that can be adopted to improve biogas production from the inoculum perspective: (i) inoculum mixing and (ii) inoculum pretreatment. Regarding CW, only the study by El Achkar et al. [56] addresses the pretreatment of the inoculum using ultrasound. These authors took cow manure as an inoculum and applied an energy pretreatment of 45, 90, and 180 kJ/kg, finding that the application of 90 kJ/kg was the most effective because it implied a little more than 50% production of CH_4 as compared to the production obtained with the use of 45 (low intensity) and 180 kJ/kg (high intensity), a result that was attributed to the fact that too low an intensity has partially destructive effects on microorganisms, whereas high intensity produces their severe destruction.

3.2.2. Trends Associated with the Substrate (CW)

The substrate is another key factor for the development of the anaerobic degradation process. Characteristics such as pH, total and bicarbonate alkalinity, volatile fatty acids (VFAs), nutrients, and the C/N ratio, among other variables, influence the production of biogas [66]. The next section presents findings related to studies where the substrates were mixed, and the C/N ratio and pH were controlled.

- Substrate mix

According to the systematic review, the CW anaerobic degradation has been studied mainly under the A-COD modality (See Table 2). This is probably because this modality has two advantages: (i) it increases the presence of nutrients and (ii) it increases the buffer capacity of the system [61]. Perhaps because of this, 19 articles, or about 37% of the studies, have focused on finding the best mixing ratio of the substrates (See Figure 7). It is important to mention that almost all of the studies use controls with each substrate; that is, they analyze the AD of each substrate separately (100%), and use the following mixing proportions, 75:25, 50:50, and 25:75, to cover the entire spectrum of possible configurations in order to find the best ratio (See Table 3).

Regarding the waste that has been mixed with CW, diverse studies have reported: Food waste (FW), Cow manure (CM), Rice straw (RS), Fruit and vegetables (FV), Maize silage (MS), Liquid manure (LCM), Primary sludge (PS), Waste Activated Sludge (WAS), Anaerobically digestated cattle manure (ADCM), Wastewater from oil mills (WOL), Sewage sludge (SS), Grape wastes (GW), Crude glycerol (CG), Sheep Manure (SM), Pork purin (PP), Glycerin (G), Hurds hemp (HH), Activated Sludge (AS), and Poultry Manure (PM). The evaluated mixing ratio is measured in different units (i.e., weight to weight (% w/w), volume/volume (v/v), or VS/L: gVS/L).

Concerning the temperature regime, most investigations have been developed in the optimal temperature of the mesophilic regime (35 °C) [67,68]; see Table 3. It is important to mention that successful AD studies considering fruit and vegetable residues or swine slurry as substrates were found using temperature values lower than 20 °C [69,70]. In relation to CW, there are a few investigations, such as that developed by Yamashiro et al. [71], that have studied two temperature regimes (mesophilic and thermophilic), although their objective was to make a digestate analysis to evaluate its final characteristics.

- Ratio C/N

Nutrients, especially nitrogen and phosphorus, are essential for the good performance of AD. When there is a high C/N ratio (>35), there may be problems of nutrient deficiency and low buffer capacity; whereas, if the C/N ratio is low (<18), there may be inhibition problems associated with the presence of ammonia released by compounds with a high content of nitrogen [78]. Authors such as Fernandes et al. [79] have recommended that the optimal range for the process should be between 18 and 35. However, the appropriate C/N will depend on the inoculum, substrate, pH, and temperature [80].

An investigation on this topic was developed by Gómez–Romero [59]. These authors evaluated five mixing ratios of CW:fruit vegetable and waste—FVW (% v/v CW:FVW, 100:0, 75:25, 50:50, 25:75, and 0:100), using C/N ratios of 7, 17, 21, 31, and 46, in order to identify the effect on hydrogen production. They found that the best C/N ratio was 21, that is, a 50:50 ratio (CW:FVW), which presented a buffer effect that improved the hydrogen production. It is worth mentioning that these findings are similar to those of Lu et al. [81] who reported C/N relationships of between 17 and 24 for slightly similar substrates.

Table 2. Anaerobic Degradation Studies with CW.

Waste	Mixing Ratio			pH	Temperature (°C)	Inoculum	Size reactor (L)	Source
CM, CW, and PS	50CM:40CW:10PS *			–	35.5	–	128	Riggio et al. [72]
CW and PM	75CW:25PM	50CW:50PM	25CW:75PM *	–	37	WWTP fed with agricultural waste	5	Carlini et al. [73]
PS, CWF, CWS, CM	100PS 100PS:30CWF:10CM 100PS:70CWF:10CM 100PS:50CWF:10CM	100PS:50CWF:1CM 100PS:30CWF:10CM 100PS:30CWS:10CM 100PS:30CWS:1CM	100PS:70CWS:10CM 100PS:70CWS:1CM ***	–	37	Primary sludge digester WWTP	2	Brown et al. [74]
CW, ULVA	0ULVA:100CW 50ULVA:50CW	25ULVA:75CW 75ULVA:25CW	100ULVA:0CW *	pH adjusted with NaOH	35	Sewage from WWTP	2	Jung et al. [57]
CW, AIW and MS	60AIW:20CW:20MS	40:AIW: 20CM:20CW:20MS *		7.8–8.0	40	–	–	Muscolo et al. [41]
CW	–			–	37	Cattle slurry	0.1	Escalante et al. [14]
CW, SS, FW, CG, CM, and GW	100SS 95SS:5GR 90SS:10CW	95SS:5FW 95SS:5CG 90SS:5CM:5CG	90SS:5FW:5CG **	–	35	–	3	Maragkaki et al. [54]
AS and mix CW with FW	100AS:0 CW-FW 90 AS:10 CW-FW	95AS:5CW-FW 85AS:15 CW-FW		7	36	Sewage from WWTP	1	Hallaji et al. [75]
CW and PP	0CW:100PP 25CW:75PP	50CW:50PP 75CW:25PP	100CW:0PP *	6.5, 7.0, 7.5, 8.0, 8.5 with NaOH or HCl	35	Treated pig slurry	0.1	Marchetti et al. [76]
CW and G	100CW:0G 98CW:2G	96CW:4G 88CW:12G *		–	50–55	UASB reactor treating vinasse	5.6	De Albuquerque et al. [15]
CW and HH	70CW:30HH	30CW:70HH *		–	36–38	Digester treating buffalo manure	0.1	Papirio et al. [16]
OMW, CW, and LCM	55OMW:40CW:5 LCM	50LCM:50OMW ***	50OMW:50CW	–	35	–	0.75 and 4	Vavouraki et al. [55]
SS and CW	100SS:0CW 50SS:50CW	60SS:40CW 40SS:60CW	25SS:75CW 0SS:100CW **	–	30	Sewage sludge from WWTP of the brewery	0.12	Iglesias-Iglesias et al. [77]

Note: ADCM: Anaerobically digestated cattle manure, AIW: Agricultural waste, AS: Activated Sludge, CG: Crude glycerol, CM: Cow manure, CW: Cheese whey, CWF: Cheese whey fresh, G: Glycerin, GR: Grape residues, HH: Hurds hemp, PM: Poultry Manure, PP: Pork Purin, PS: *P. Australis*, FW: Food waste, FV: Fruit and vegetables, GW: Grape waste, LCM: Liquid manure, MS: Maize silage, OMW: Olive mills wastewater, PS: Primary sludge, RS: Rice straw, SS: Sewage sludge, ULVA: Sea lettuce, WAS: Waste Activated Sludge, WWTP: Wastewater treatment plant. * % weight/ weight, ** volume/ volume *** SV/L: gSV/L.

- pH

pH is a key variable that requires constant monitoring in anaerobic processes [66], especially when the substrates to be digested have acidic conditions such as with CW. This substrate tends to overload the VFAs [50], which leads to a decrease in pH, inhibiting the activity of microorganisms such as Methanogenic Archeas [82]. Traditionally, when the substrates are acidic, alkalinizers, such as sodium hydroxide NaOH or calcium carbonate CaCO3 are added to the digesters. These measures serve temporarily but do not guarantee that the buffering effect will last throughout the process. In addition, these substances cannot be recovered and thus imply increasing costs.

In this string of research, Flores-Mendoza et al. [83] evaluated the pH (6.0, 7.0, and 8.0), the S/I ratio (4.1, 10.2, and 16.4), and the temperature (20, 30, and 40 °C) of the CW AD process through the response surface analysis. They found that the best operational conditions of pH (adjusted with NaOH), the S/I ratio, and the temperature are 8.0, 4.1, and 40 °C, respectively. Likewise, these authors established that pH is an important variable and that it is necessary to add buffer capacity to the system to promote the growth and development of microbial communities. On the other hand, Charalambous and Vyrides [60] investigated two sources of iron: (i) commercial iron powder and (ii) scrap iron in zero valence powder, in concentrations of 25, 50, and 100 g/L, to increase the pH and the production of methane through the transformation of the VFAs. These researchers concluded that the best concentrations of zero valence iron dust and scrap iron are 25 and 50 g/L, respectively, as they increased the CH_4 production by approximately 95%, which would reduce the use of the NaOH.

Marchetti and Vasmara [76], evaluated the pH values of 6.5, 7.0, 7.5, 8.0, and 8.5, adjusting with NaOH or HCl, and mixing proportions between CW and PP of 0CW:100PP; 25CW:75PP; 50CW:50PP; 75CW:25PP; and 100CW:0PP. They found that the pH influences the final product obtained (H_2, CH_4, or VFAs). In addition, they established that PP is not the best substrate to develop A-COD with CW as the degradation path with this substrate deviates towards acidogenesis and consequently does not produce CH_4. Through this combination of substrates, H_2 or VFAs can be obtained. If the purpose of the A-COD is to obtain H_2, it is recommended to develop the process at a neutral pH.

3.2.3. Trends Associated with the Digestate

Digestate is a semi-solid material obtained as a by-product of anaerobic degradation. It has soil-amendment characteristics due to the presence of nutrients such as potassium, phosphorus, and nitrogen, elements of significant importance for the development and growth of plants [84]. Among the studies with the digestate involving CW are the works of Muscolo et al. [41] and Escalante et al. [14].

Muscolo et al. [41] investigated how the mixing ratio influenced the digestate obtained and the soil characteristics, evaluating two mixtures with AIW, CW, CM, and MS with the following proportions 60AIW:20CW:20MS and 40AIW:20CM:20CW:20MS (% w/w), separated into liquid and solid fractions. These authors found that not only the type of substrate influenced the characteristics of the digestate, but also that some soil parameters, such as organic matter and soil catalase, can be affected. They also determined that the solid fraction increases humification rates, and the liquid fraction can be used in exchange for conventional irrigation water.

Escalante et al. [14] evaluated the energy and precipitation potential of struvite (precipitation of ammonium magnesium phosphate hexahydrate—$MgNH_4\ PO_4\ 6H_2O$), which is naturally precipitated when the molar ratio of $Mg{:}NH_4{:}PO_4$ is higher than 1:1:1. Struvite is a beneficial material for improving soils since it is less soluble in water as compared to commercial inorganic fertilizers [85]. This implies less loss due to nutrient dispersion. The authors identified that the digestate obtained from CW AD can generate between 8.47 and 10.37 g of struvite/L CW with the addition of Mg. In this way, not only biogas, but also a soil improver containing nutrients that would help reduce dependence on inorganic fertilizer, can be obtained.

It is important to clarify that the soil improver must be carefully analyzed before it is applied in cultures because it is not always stabilized. The adequate HRT for the stabilization of the digestate is not the same as that required to achieve the maximum production of CH_4 [84]. Moreover, it is important to consider that the use of soil improver may emit odors and favor the presence of toxic organic compounds. Additionally, this material in many cases has problems due to the high presence of pathogens, generally when the substrate has been degraded under mesophilic temperature regimes [45].

3.2.4. Trends Associated with the Related Microbiology Processes

AD or A-COD is composed of four phases: (i) hydrolysis (fractionation of complex polymers), (ii) acidogenesis (fermentation of sugars, amino acids, and fatty acids to VFAs), (iii) acetogenesis (conversion of VFAs into acetate and H_2), and (iv) methanogenesis (production of CH_4 from acetate and H_2) (see Figure 8). Each of these stages depends on the previous one as the by-products obtained in one stage are the inputs of the next. Therefore, knowledge regarding the microorganisms associated with the process is essential to better understand the relationship that exists between the intermediate products (i.e., VFAs) and the final products (i.e., H_2 and CH_4). However, the microbiological conditions and aspects such as pH are characteristics of the bacterial group and the substrate used [86].

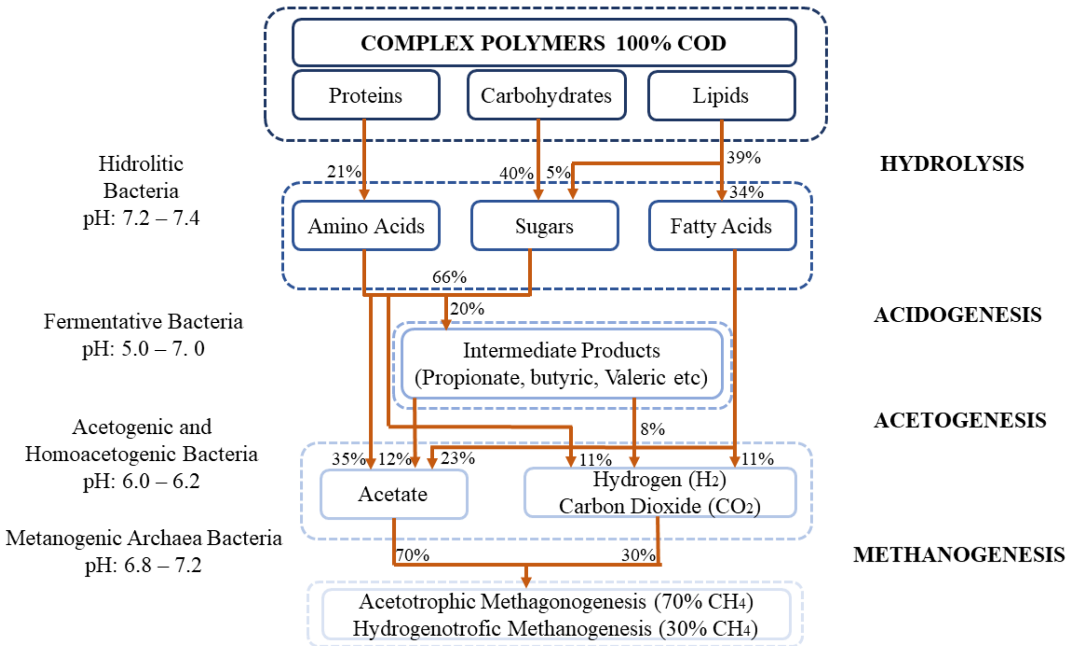

Figure 8. Phases of the anaerobic digestion process, adapted from Mata-Álvarez [87] and Nayono [88].

As the limiting step in most cases of anaerobic degradation processes is hydrolysis [61], authors such as Liew et al. [51] have found that the inclusion of between 1% and 2% (w/w) of enzymes is key to improving the performance of the step and therefore of the process; however, a barrier in this regard is the cost; so, the development of enzymes with these characteristics is of great interest.

Concerning the microbiology processes, Pagliano et al. [89] point out that the microbial dynamics in the reactor will be predominantly influenced by the characteristics of the inoculum, substrates, and operating conditions. These authors worked with CW and CM and identified that the main source of CH_4 production was the hydrogenotrophic pathway because of the greater presence of the genus Mathanoculleus, which was influenced by the addition of granulated manure that allowed the development of the Archeas.

Jaimes-Estévez et al. [28] found that in tubular reactors, where they treated CW and CM in A-COD at different organic loading rates of OLR (0.5, 1.0, and 1.5 kg_{CDO}/m^3d^{-1}), there was a balance between the hydrogenotrophic methanogens and acetoclastics for the OLR of 0.5 kg_{CDO}/m^3d^{-1}; in the intermediate OLR (1.0 kg_{CDO}/m^3d^{-1}), acetoclastic bacteria predominated, but there were pH problems as the TRH progressed. For this reason, they added an alkalinizer. Finally, in the load of 1.5 kg_{CDO}/m^3d^{-1} there was a stratification of microorganisms as initially, in the first part of the axis, no methanogens were found, but their presence was later detected.

3.2.5. Trends Associated with Reactor Configuration

The configuration and operation of the reactor influence biogas production. The literature review shows several studies that have been developed around the type of reactor, the reactor bed, the number of stages, the organic load, and the hydraulic retention time. The findings in each of them are presented below.

- Type of reactor and bed

The upflow anaerobic sludge mantle reactor (UASB) and the anaerobic membrane bioreactors (AnMBR) are some of the reactors used for the AD processes. UASBs are suitable for the treatment of high organic-resistance wastewater, such as CW, because of their low use of energy and their suitability for operating with high organic loads OLR [90], whilst the AnMBR are widely used for substrates with high organic loads. For its part, the reactor bed is a factor that is very useful for the microorganisms´ growth as there they can adhere and proliferate, generating a greater production of biogas [91].

Rico et al. [92] studied the A-COD of CW with CM in a one-stage UASB reactor with a re-circulation of effluents, finding that (i) the maximum rate that can be evaluated under this combination was 28.7 $kgCOD/m^3d^{-1}$ (a ratio of 60CW:40CM) and (ii) the mixture of these substrates can be maintained with a maximum of 2.2 HRT. Fernández et al. [53], evaluated the use of the AnMBR system for CW AD, using one and two stages, finding that, unlike the one-stage system, the two-stage system produced a greater amount of methane gas and greater microbial diversity, possibly associated with salinity. However, this system presented instabilities given the salt concentrations.

Another type of reactor that has been used for the treatment of CW with CS (75:25) is the AnMBR. Ribera-Pi et al. [52] observed the removal of 91% of the COD added to this type of reactor, which emphasizes the use of the AnMBR for the degradation of CW. These authors highlight that the pH adjustment to 7 using NaOH was important, but that, as the inoculum adapted to the substrates, the required alkalizing concentration decreased (6.2 meq $NaOH/g_{COD}$). Likewise, they identified that as AnMBR does not remove salts from the effluent, the liquid cannot be used for agricultural applications without an additional process. Other authors, such as Lovato et al. [93], used AnMBR reactors to evaluate CW A-COD with glycerin (100:0, 75:25, 50:50, 25:75, and 0:100) and found that the best ratio was 75:25. Likewise, they were able to eliminate up to 89% of the COD, which represents an increase in the individual digestion of CW and glycerine of 9% and 30%, respectively. These findings confirm the effectiveness of this type of reactor.

Finally, Sánchez-Sánchez et al. [94] studied the material of the reactor bed to increase the fixation of the bacteria. For this, they used as substrate almond shell, walnut shell, kenaf fiber, and charcoal (all crushed) in a mixture of sheep manure—SM:CW (% w/w) of 20SM:80CW. As a result, they established that a charcoal bed was the best option for the fixation of biogas-producing bacteria. This bed increased biogas production by 27.8% as compared to the control. In addition, charcoal promoted a higher CH_4 production as compared to the almond shell, walnut shell, and kenaf fiber, mainly because these materials had inhibitory problems due to substances such as sulfates or VFAs.

- Stages

Single-phase AD is developed in a single reactor; that is, the four stages are developed in the same space even when the conditions (i.e., pH) vary between them. This means that, depending on the substrate, problems may arise as the result of the accumulation of VFAs, which triggers the inhibition of some bacterial groups (i.e., methanogenic Archeas) [61]. Erdirencelebi [95] investigated a three-stage reactor with effluent recycling for CW degradation. His findings indicate that the multi-staged system is efficient because the third phase compensates for the poor performance of the one-stage. Additionally, the pH and alkalinity levels are kept balanced for the entire process, which explains why the sequential system with effluent recirculation represents a good option for high levels of fat treatment. Diamantis et al. [90] demonstrated that a coupled continuous stirred-tank reactor CSTR-UASB two-stage system produces better COD removal (90%) than a one-stage UASB system. This confirms the usefulness and efficiency of the two stages in digestion processes; that is, those AD processes in which the two phases take place in different reactors guarantee the best conditions for each phase.

In biphasic AD, the stages of acidogenesis and methanogenesis are divided so that each microbial group develops according to its optimal conditions [96]. The use of this phase division presents advantages, such as (i) a stable system, (ii) a synergistic effect on the microorganisms, (iii) a lower HRT, and (iv) the obtaining of a greater number of products (VFAs, H_2, CH_4, and (v) achieving nutrient balance, among others [93,97,98].

- Organic Loading Rate (OLR)

According to Wang et al. [99], the organic load supplied to the reactor is also a key aspect for the performance of the process. Thus, biogas production depends on the OLR.

However, very high organic loads could accelerate the production of VFAs and inhibit the process as a result of the decrease in pH. Moguel-Castañeda et al. [100] investigated the increase in OLR of 2.5 g_{COD} $L^{-1}d^{-1}$ every 30 days until reaching 10 g_{COD} $L^{-1}d^{-1}$. They found that those high loads (>6 g_{COD} $L^{-1}d^{-1}$) promoted the production of biogas; however, the methane can also decrease, and in that case, the process becomes more unstable. These authors concluded that the best load was 5 g_{COD} $L^{-1}d^{-1}$. For their part, Calero et al. [101] compared the performance of OLR in a UASB reactor and a Sequencing batch reactor (SBR) to obtain VFAs from CW. They found that although the degradation reached in both reactors was similar, with 98% of the COD at an OLR of 2.7 g_{COD} $L^{-1}d^{-1}$ 1 and 97% of the COD at an OLR of 15.1 g_{COD} $L^{-1}d^{-1}$ for the SBR and the UASB, respectively, the UASB supported greater organic loads than the SBR as the maximum acidification occurred at lower loads in the SBR as compared to the USB.

- Hydraulic Retention Time (HRT)

HRT is defined as the time that elapses between the entry of a particle and its exit. The variation of the HRT will depend on the substrate and other variables inherent to the process (i.e., temperature and agitation) [102]. The HRT required by simple reactors in mesophilic conditions to keep the acidogenic and methanogenic archaebacteria balanced is around 15 days [103]. Dareioti and Kornaros [49] studied the effect of the HRT of A-COD at 30 °C between ensiled sorghum (ES), CW, and CM in a 55:45:5 v/v ratio in two CSTR reactors to improve the acidogenesis and methanogenesis processes. While periods of 5, 3, 1, 0.75, and 0.5 days were analyzed in the first reactor, the second one was operated considering 24, 16, and 12 days. It was determined that for these reactor configurations the optimal time for each reactor was 0.5 and 16 days, correspondingly, with the highest rates of H_2 and CH_4. This is slightly similar to the findings of Kothari et al. [104] who concluded that HRT can range between 10 and 40 days. On the other hand, Da Silva et al. [105] found that the HRT of dairy effluents can be close to 0.33 days.

A summary of the main findings is presented in Table 3.

Table 3. Summary of the main findings of Section 3.2.

Factor	Variable	Conclusion	Source
Inoculum		The inoculum most used is from WWTP. Mixing pretreatment inoculum can improve the biogas production.	El Achkar et al. [56]; Koch et al. [65]
Substrate	**Substrate mix**	Increases the presence of nutrients and the buffer capacity of the system.	Cárdenas-Cleves et al. [61]
		One option to mix the substrates is 75:25, 50:50, 25:75 to cover the entire spectrum of possible configurations to find the best ratio.	
	C/N	When C/N ratio is high (>35), there may be problems of nutrient deficiency and/or low buffer capacity; in contrast, if the C/N ratio is low (<18), there may be inhibition problems associated with the presence of ammonia.	Parawira [78]; Fernandes et al. [79]
	pH	The variable that requires constant monitoring in the anaerobic process. It is better to be near to neutrality and use NaOH or CaCO3 to increase pH.	Mirmohamadsadeghi et al. [66]; Marchetti and Vasmara, [76]
Digestate		The type of substrate influenced the characteristics of the digestate and some soil parameters, such as organic matter and soil catalase. Through digestate from CW, struvite can be obtained, which is better than inorganic fertilizers.	Musculo et al. [41]; Escalante et al. [14]
Microbiology		Microbial dynamics in the reactor will be predominantly influenced by the characteristics of the inoculum, substrates, and operating conditions.	Pagliano et al. [89]
Reactor configuration	**Type and bed**	UASBs are suitable for the treatment of high organic-resistance wastewater such as CW because of their low use of energy and their suitability for operating with high OLR. AnMBR does not remove salts from the effluent; the liquid cannot be used for agricultural applications without an additional process. The charcoal bed was the best option for the fixation of biogas-producing bacteria.	Ribera-Pi et al. [52]; Diamantis et al. [90]; Sánchez-Sánchez et al. [94]
	Stages	Depending on the substrate (in a single phase), problems may arise as the result of the accumulation of VFAs, which triggers inhibition of some bacteria. In biphasic AD, it presents advantages, such as (i) a stable system, (ii) a synergistic effect on microorganisms, (iii) a lower HRT, (iv) the obtaining of a greater number of products (VFAs, H2, CH4), and (v) achieving nutrient balance,	Jin et al. [96]; Begum et al. [97]; Negri et al. [98]
	OLR	Very high organic loads could accelerate the production of VFAs and inhibit the process as a result of the decrease in pH.	Wang et al. [99]
		UASB supports greater organic loads than the SBR as the maximum acidification occurs at lower loads in the SBR as compared to the USB	Calero et al. [101]
	HRT	HRT can range between 10 and 40 days.	Dareioti and Kornaros, [49]; Kothari et al. [104]

Note: AnMBR: Anaerobic membrane bioreactors, C/N: Carbon/Nitrogen ratio, CW: Cheese whey, HRT: Hydraulic retention time, OLR: Organic loading rate, UASB: Upflow anaerobic sludge mantle reactor, VFAs: volatile fatty acids, WWTP: Wastewater treatment plant.

3.3. Advances in the Inclusion of CE in the Biological Use by AD/ACOD of CW

The studies that include the CE in their analysis are scarce. Only 8 of the selected 52 studies tangentially addressed the CE. However, authors such as Papirio et al. [16] carried out a technical–economic study comparing the AD process of Hurds Hemp (HH) and that of A-COD with CW and Hurds Hemp. They found that the combination of the substrates has a synergistic effect as there is an increase in the production of CH_4 of 10.7% as compared to the production of CH_4 using the AD of only HH. Additionally, by incorporating the two waste streams into the process, they found net gains of 6124 EUR/ha as compared to 3929 EUR/ha when using only HH.

Kassongo et al. [42], in a study on A-COD to treat grape marc (GM), found that in using a ratio of 75:25 (GM:CW w/w) a removal of more than 21.18%, in the total COD was obtained, compared to just digesting grape wastes (GM). Therefore, these residues are useful for energy recovery and contribute to the sustainability of the wine fermentation process. In another work with the same waste and ratio, Kassongo et al. [48] found that through this combination it was possible to obtain 0.601 m^3 of biogas kg^{-1} VS and 0.363 m^3 of CH_4 kg^{-1} VS, which demonstrates the possibility of reducing the use of fossil fuels and the inclusion of the CE through anaerobic processes, as well as avoiding the production of 482,000 Mt of CO_2 equivalents.

Likewise, Ribera-Pi et al. [52] investigated the A-COD of CW and CM in an AnMBR reactor and found that on average 91% of the COD was eliminated. The methane production was between 51% and 73%, recovering an average energy value of 2.4 kWh/kg COD eliminated. In addition, the process has the potential to recover water, for which electrolysis with monovalent membranes must be used.

For their part, Gameiro et al. [43] developed a CW AD process where they introduced inorganic polymer spheres based on red mud to regulate the pH. The researchers found that the spheres not only buffered the pH, but also increased the methane yield (90%), making it possible to substitute typical alkalinizers, that is, virgin raw materials, showing different alternatives for the application of CE.

Researchers such as Muscolo et al. [41] and Escalante et al. [14] are among the few who have focused on the study of digestate to potentiate the anaerobic degradation. Their research focuses on the study of this by-product which, at an industrial level, can impact the operational cost. They found that the characteristics of the digestates are influenced by the substrates that are degraded and that it is possible to obtain struvite through the digestate, respectively.

Dolman et al. [26] evaluated the reduction of environmental impacts from nutrient recycling (i.e., adding manure to the soil) in dairy farms in the Netherlands and found that farms that recycle nutrients require less energy due to the use of aerial manure application techniques that minimize the use of the fossil fuels required by conventional techniques. Kilkiş and Kılkış [106] proposed a methodology to compare different energy and biogas utilization schemes on a dairy farm in Turkey. Rosa [107] analyzed how to produce Polyhydroxy-alkanoates from whey in cheese-producing farms in Italy, and Stanchev et al. [27] developed an approach to measure the environmental performance of the anaerobic treatment of effluents from the production on a UK dairy farm.

Although there is evidence that shows an approximation of the dairy sector move towards the circular economy, there are still no reports analyzing case studies where opportunities for improvement are identified, which could be implemented by companies of different sizes, therefore improving their sustainability.

4. Research and Reflection Trends

The systematic review resulted in the identification of five factors with high relevance in the CW degradation process: inoculum, substrate, digestate analysis, microbiological analysis, and reactor configuration. Each factor has different associated variables. It was observed that there are variables of incidence in the process, such as (i) substrate pretreatment, (ii) inoculum, (iii) temperature in the psychrophilic range, (iv) aspects of the reactor such as the number of stages, and (v) the scale of the reactor, which have scarcely been addressed in the literature.

Concerning the reactors´ configuration and capacity, about 93% of the articles on AD were developed in one stage, and 89% of the articles developed BMP, considering a capacity of the reactors lower than 128 L. These aspects represent knowledge gaps that can be addressed in future research and that have been identified in similar literature reviews with FW [45,108].

Concerning substrates, cattle manure has been used in many (38%) of the studies that were found about CW. On the one hand, cattle manure has been used as a co-substrate. Moreover, it has been used as an inoculum; this may be due to the affinity that exists between the CW and the CM as they are part of the same production process. This implies easy access to the resources for the AD, and relatively simple implementation of the process, important aspects that make viable this management alternative [109].

Regarding the parameters, it was identified that few studies address them jointly, which can lead to errors as the possible interaction between the variables might be ignored when the variables are studied individually [63]. This finding was also highlighted by Casallas-Ojeda et al. [45] in their AD technology surveillance with FW.

Regarding the CE, there is scarce research on the biological use with AD/A-COD. Therefore, the development of analysis within the framework of the CE, starting from anaerobic degradation as a utilization option, would allow the identification of improvement opportunities that may apply to different sizes of dairy industries, especially in South America where it is expected that the milk production will increase substantially. The incorporation of the biogas, either for thermal uses or for electricity generation, in the dairy industry processes, in conjunction with the use of the digestate for the growth and development of the pasture consumed by livestock, has the potential to close the productive cycle, probably obtaining economic savings. The analysis of these synergies could contribute to the implementation of full-scale AD plants that use CW as a substrate, as well as food residues [20].

In short, AD is one of the forms of waste management that enhances the use and recovery of organic waste, generating value-added products. AD has the potential to contribute to the mitigation of environmental impacts, such as the production of GHG and the contamination of surface and underground water. In addition, it is also possible to recover degraded soils through the digestate contributing to the closure of the AD cycle and, consequently, enhancing the approach to the CE principles in the milk production process. AD can also contribute to the mitigation of gases such as CO_2 which are derived from the production of inorganic fertilizers [13]. Furthermore, the use of the digestate would not only help the environment for the reasons already mentioned but would also contribute to stabilizing the prices of products using fertilizers that in many cases vary as a consequence of the prices of imports of inorganic fertilizers.

5. Conclusions

The anaerobic degradation of cheese whey is an alternative for waste management and recovery that allows the closure of the productive cycle of cheese production. In addition, it contributes to the proper management of the waste that is produced worldwide. Europe is the place where most of the articles concerning the use of the CW were found. At the country level, the leaders are Italy and Greece. In South America, anaerobic digestion takes place mainly in the fixed-dome and tubular reactors and its main substrate is manure. Each substrate-co-substrate(s) and inoculum(s) combination has its specific characteristics that make each process unique. Thus, the different variables involved in the process must be studied together to enable a holistic analysis. Studying the incidence of variables simultaneously is beneficial not only in terms of finding potential interactions but also in terms of saving resources and time. The application of anaerobic digestion in the dairy sector opens an opportunity for the implementation of the circular economy that can be beneficial not only for the environment but also for the producers who will see savings in their investment/operating costs.

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Abbreviations

A-COD	Anaerobic Codigestion
AD	Anaerobic Digestion
ADCM	Anaerobically Digestated Cattle Manure
AIW	Agricultural waste
AS	Activated Sludge
AnMBR	Anaerobic Membrane Bioreactors
BMP	Biochemical Methane Potential
$CaCO_3$	Calcium Carbonate
CE	Circular Economy
CG	Crude Glycerol
COD	Chemical Oxygen Demand
CH_4	Methane
CM	Cow Manure
C/N	Carbon/Nitrogen Ratio
CSTR	Continuous Stirred-Tank Reactor
CW	Cheese Whey
CWF	Cheese Whey Fresh
FAO	Food and Agricultural Organization
FV	Fruit and Vegetables
FVW	Fruit Vegetable and Waste
FW	Food Waste
G	Glycerin
$g_{COD}\ L^{-1}d^{-1}$	Grams of Chemical Oxygen Demand per Litre.Día
GHG	Greenhouse Gas
GM	Grape Marc
GW	Grape Wastes
GR	Grape Residues

H_2	Hydrogen
Hydraulic retention time	Hrt
HCl	Chlorhydric Acid
HH	Hurds Hemp
kg_{CDO}/m^3d^{-1}	Kilogram of chemical oxigen demand/cubic meter.day
kJ/kg	kilojoule/kilogram
LA	Latin America
LCM	Liquid Manure
$MgNH_4\ PO_4\ 6H_2O$	Ammonium Magnesium Phosphate Hexahydrate
MS	Maize Silage
NaOH	Sodium Hydroxide
NTK	Total Kjeldahl Nitrogen
OLR	Organic Loading Rate
OMW	Olive Mills Wastewater
PM	Poultry Manure
PP	Pork Purin
PS	Primary Sludge
RS	Rice Straw
SBR	Sequencing Batch Reactor
SDG	Sustainable Development Goals
SM	Sheep Manure
SS	Sewage Sludge
UASB	Upflow Anaerobic Sludge Mantle Reactor
ULVA	Sea Lettuce
VFAs	Volatile Fatty Acids
VS/L: gVS/L	Volatile Solids/Litre: Grams Volatile Solids/Litre
v/v	Volume/Volume
WAS	Waste Activated Sludge
WOL	Wastewater From Oil Mills
w/w	Weight To Weight
WWTP	Wastewater Treatment Plants

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