Heliyon 8 (2022) e11174

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Review article

Research trends and strategies for the improvement of anaerobic digestion of food waste in psychrophilic temperatures conditions

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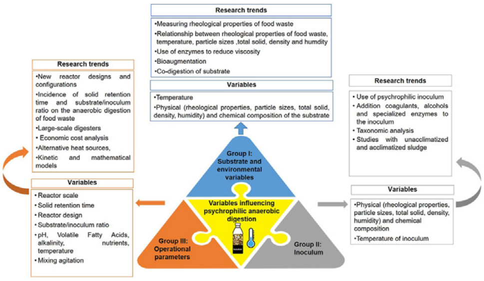
HIGHLIGHTS

- Temperature has a great influence on anaerobic digestion of food waste (FW-AD).
- Studies on the psychrophilic condition are limited, warranting further research.
- Physical properties of the substrate and inoculum influence psychrophilic FW-AD.
- The use of inocula adapted to low temperatures could increase biogas production.
- Changes in reactor configurations could improve biogas yield at low temperature.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Anaerobic digestion
Bioenergy
Food waste
Mesophilic temperature
Psychrophilic temperature
Thermophilic temperature

ABSTRACT

The organic fraction of municipal solid waste is mainly composed of food waste (FW), and traditional disposal practices for this fraction are generally considered to have negative environmental and economic impacts. However, the organic characteristics of this fraction could also be exploited through the anaerobic digestion of FW (FW-AD), which represents unique advantages, including the reduction of the area required for final disposal and environmental pollution and the same time the generation of renewable energy (mainly methane gas), and a by-product for agricultural use (digestate) due to its high nutrient content. Although approximately 88% of the world's population resides in areas with temperatures below 8 °C, psychrophilic conditions (temperatures below 20 °C) have hardly been studied, while mesophilic (66%) and thermophilic (27%) ranges were found to be more common than psychrophilic FW-AD (7%). The latter condition could decrease microbial activity and organic matter removal, which could affect biogas production and even make AD unfeasible. To improve the efficiency of the psychrophilic FW-AD process, there are strategies such as: measurement of physical properties as particle size, rheological characteristics (viscosity, consistency index and substrate behavior index), density and humidity, bioaugmentation and co-digestion with other substrates, use of inocula with psychrophilic methanogenic communities, reactor heating and modification of reactor configurations. However, these variables have hardly been studied in the context of psychrophilic conditions and future research should focus on evaluating the influence of these variables on FW-AD under psychrophilic conditions. Through a bibliometric analysis, this paper has described and analyzed the FW-AD process, with a focus on the psychrophilic conditions (<20 °C) so as to identify advances and future research trends, as well as determine strategies toward improving the anaerobic process under low temperature conditions.

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https://doi.org/10.1016/j.heliyon.2022.e11174
Received 26 June 2022; Received in revised form 9 September 2022; Accepted 17 October 2022

1. Introduction

Domestic, commercial, industrial, and service activities generate municipal solid waste (MSW), which is composed mostly of organic waste [1]. Food waste (FW) represents between 40%–70% of MSW [1, 2], whose composition varies according to the type of waste and its components [3], that is generally characterized by high contents of organic matter, moisture, and nutrients and easily acidifiable [4]. FW contains mainly raw (50%–70%: vegetables and fruit peels) and cooked wastes (35%: leftovers of prepared food, such as cooked rice and meat) [5, 6].

An estimated 33% of the food produced globally for human consumption is lost or wasted through the food supply chain [7], representing 1600 Mt of FW generated each year [8, 9], with a generation of FW per person of 0.160–0.295 t [10]. When FW is disposed in landfills [7], considerable amounts of greenhouse gases (GHGs) are generated [11], whose emission into the atmosphere contributes to global warming and can generate unpleasant odors and toxic gases (volatile organic compounds) [6], contaminate water bodies via the production of leachates, and also contributes to the reduction of the capacity in units of time that the landfill will operate and continue receiving solid wastes [12].

When FW is exploited trough strategies such as anaerobic digestion (AD) [13], economic and environmental benefits are generated via the avoidance of inadequate final disposal. AD could reduce GHGs emissions by up to 200 Mt/year [14], contributing to the sustainable development of society [15]. This technique is aligned with current trends oriented toward the use of green and clean energy technologies [16].

AD refers to a process of organic matter degradation in which complex molecules are spontaneously reduced to their individual energy components without energy supply via the action of microorganisms in the absence of molecular oxygen [17, 18]. In this case, the complex compounds of the substrate are transformed into digestate and mainly biogas, that is a renewable type of bioenergy with energy yields of 5.5–7.0 kWh/m^3; it can be used as a heating fuel and for electricity/heat co-generation [19].

Research in technologies such as FW-AD has gained increased importance over the last few years, as reflected by the recent increase in number of publications on the subject [13, 20]. Despite having large fractions of renewable sources as substrates, such as wastewater and sludge from wastewater treatment plants, MSW, and agricultural and crop residues [21], 770 million people worldwide do not have access to electricity, and 2.4 billion inhabitants continue to use traditional biomass (e.g., firewood, coal, dry manure) as an energy source [2, 22].

Temperature is a variable that remarkably affects the microbial growth rate and degradation of organic matter [23]. As such, it could also affect the yield of methane (CH4) in the AD process because temperature may influence the physical parameters of the substrate, including its surface tension, viscosity, and mass transfer properties [24]. Changes in these properties could, in turn, influence the physicochemical characteristics of the substrate, assimilation, and transport of the substrate by microorganisms when the reactor is operated; thus, the production of CH4 may be affected [24, 25]. Additionally temperature affects the operation of landfills in aspects such as decreases in the efficiency of the system, longer decomposition times of the organic matter and greater requirements of the final disposal areas [26].

In general, three temperature ranges have been established in studies of biological processes: thermophilic (46–60 °C; usually 45 °C), mesophilic (20–45 °C; usually 35 °C), and psychrophilic (10–20 °C; usually 20 °C) [24, 27]. Most previous FW-AD studies has been carried out under mesophilic and thermophilic conditions, on contrast, the psychrophilic condition has been the least studied [24]. The thermophilic process is more sensitive to environmental variations than the mesophilic process and requires external energy inputs [28, 29].

Low temperatures can lead to decreased efficiency during AD, thereby causing the depletion of cellular energy, leakage of intracellular substances, incomplete lysis, low efficiency of organic matter removal, accumulation of volatile fatty acids (VFAs), and decreased biogas production and quality [30]. These issues could render the process physically and financially unviable because energy is required to heat the reactors and maintain the required temperature [29, 30].

Table 1. Search strings for the database searches.

SCOPUS
(TITLE-ABS-KEY (("Food Waste" OR "Kitchen Waste" OR "Food Residue" OR "Kitchen Residue" OR "Biowaste" OR "Solid Waste" OR ″ Organic fraction of municipal solid waste")) AND TITLE-ABS-KEY ("Anaerobic digestion") AND TITLE-ABS-KEY (("Temperature Effect"OR "Cold region" OR "Psychrophilic Temperature Effect" OR "Psychrophilic temperature" OR "Psychrophilic Anaerobic Digestion" OR "Psychrophilic Microorganisms" OR "Psychrophilic anaerobes" OR "Psychrophilic methanogenesis" OR "Psychrophilic Range" OR "Psychrophilic digestion" OR "Psychrophilic Conditions" OR "Psychrophilic Biomethanation" OR "Low temperature anaerobic digestion"OR "Mesophilic temperature" OR "Termophilic Temperature")) AND TITLE-ABS-KEY (("Methane" OR "Biogas" OR "Renewable Energy" OR "Waste to energy" OR "Waste Bioconversion" OR "Biomethane potential" OR "Biochemical Methane Potential" OR "Methane Potential" OR "Biogas reactor" OR "Operational Parameters" OR "Incidence parameters")))
WOS
"Food Waste" OR "Kitchen Waste" OR "Food Residue" OR "Kitchen Residue" OR "Biowaste" OR "Solid Waste" OR ″ Organic fraction of municipal solid waste" AND "Anaerobic digestion" OR "Psychrophilic Anaerobic Digestion" OR "Low temperature Anaerobic Digestion"AND "Cold region" OR "Psychrophilic Temperature Effect" OR "Psychrophilic temperature" OR "Psychrophilic Microorganisms" OR "Psychrophilic anaerobes" OR "Psychrophilic methanogenesis" OR "Psychrophilic Range" OR "Psychrophilic digestion" OR "Psychrophilic Conditions" OR "Psychrophilic Biomethanation OR "Mesophilic temperature" OR "Termophilic temperature"AND "Methane" OR "Biogas" OR "Renewable Energy" OR "Waste to energy" OR "Waste Bioconversion" OR "Biomethanation"OR "Biomethane potential" OR "Biochemical Methane Potential" OR "Methane Potential" OR "Biogas reactor" OR "Operational Parameters" OR "Incidence parameters"
SciELO
("Anaerobic digestion" OR "digestión anaerobia" OR "digestão anaeróbica") AND ("resíduos alimentares" OR "Food Waste" OR "residuos de alimentos" OR "desperdícios de cozinha" OR "Kitchen waste" OR "Biowaste" OR "Biorresiduos de origen municipal" OR "Resíduos Sólidos urbanos" OR "Municipal solid waste" OR "Residuos sólidos municipales" OR "Fração orgânica dos resíduos sólidos urbanos" OR "Organic fraction of municipal solid waste" OR "Fracción orgánica residuos sólidos municipales") AND ("Psychrophilic temperature" OR "Temperatura psicrofilica" OR "Temperatura psicofílica" OR "Gama psicrófila" OR "Psychrophilic Range" OR "Rango psicrofílico" OR "Condiciones psicofílicas" OR "Psychrophilic Conditions" OR "Condiciones psicrofílicas" OR "Biometanação Psicrófila" OR "Psychrophilic Biomethanation" OR "Biometanización psicrofílica"OR "Digestión psicofílica" OR "Psychrophilic digestion" OR "digestíon psicrofílica") OR ("Mesophilic temperature" OR "Temperatura mesofilica" OR "temperatura mesofílica") OR ("Thermophilic temperature" OR "Temperatura termofílica" OR "temperatura termofílica") OR ("Temperature effect" OR "efecto de la temperatura")

The articles were exported from WOS in .BibTeX format, from Scopus and SciELO in .RIS format, and from Publindex in .PDF format. Total number of articles in the search was 348.

Most countries with cold climates tend to have average annual temperatures below 8 °C [31] and are in the northern hemisphere, where 88% of the world's population is located [32]. In addition, within the daily temperature fluctuation, temperatures below 0 °C can occur [33]. Authors such as Dev et al. [24] have indicated that psychrophilic AD could be the most appropriate option for these regions if its potential applications are well demonstrated.

Considering the large percentage of the world population living in cold regions, the energy generation potential from the FW-AD process and the limited number of researches under low temperatures, this paper intends to describe and analyze the FW-AD process with a focus on the psychrophilic conditions (<20 °C). Through the use of bibliometric analysis tools, there are identified aspects such as the limitations of the process, the research advances in this field, the strategies that could potentially improve the process under psychrophilic conditions, and the future research trends on that temperature condition.

2. Materials and methods

Bibliometric analysis tools were applied according to the methodologies used by authors such as Gómez-Ríos and Ramírez-Malule [34] and Casallas-Ojeda et al. [35]. The analysis of the quality and selection of the papers was based on past studies, such as Komilis et al. [34], and on the methodology "Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)" established by Mancebo et al. [36], which includes 3 stages: the identification (involving the selection of databases, and the definition of keywords and search equations), screening (analysis of articles), and inclusion (articles included for the review).

2.1. Identification

- Database selection: The Scopus and Web of Science (WOS) databases were searched for articles in the international context (English), while SciELO (English, Portuguese, and Spanish) were searched for articles in the Latin American context.
- Definition of keywords and search equation: Table 1 details the search criteria formed with specific keywords and Boolean operators. A systematic search of relevant terms in the title, abstract, and keywords of articles published between 2000 and 2021 was conducted [37, 38].

2.2. Screening

The information was loaded into Mendeley© 1.19.8 software to collate all articles into a single file and verify the existence of duplicate articles; 25 duplicates were removed from the article list and the number of reports assessed for eligibility was 323. Once the information was unified, it was exported to a file in RIS format and then loaded into VOSviewer© 1.6.15 software to obtain a keyword map.

The file that was generated in the Mendeley © 1.19.8 software was also loaded in the RefViz© 2.1.2 software (test version) to analyze the information of the articles, the analysis criteria for the selection and exclusion of studies were the number of citations and the impact of the article, most relevant authors, keywords, the content of the abstract, and the conclusions and bibliographical information [19, 34, 35]. The studies that covered the topic related to the variables that influence the FW-AD process that were identified in the keywords map and associated with the temperature were selected. From this analysis, 51 reports were excluded.

2.3. Inclusion

A total of 272 articles were included from, which information was obtained on the FW-AD process, the evolution of FW-AD over a period of time, the most and least investigated variables were identified and then classified into 3 main groups, as follows Group I: Substrate and environmental variables; Group II: Inoculum; and Group III: Operational parameters [39, 40]. From the 272 articles included, 181 were associated with FW-AD under the mesophilic condition, 69 under the thermophilic condition, and 22 corresponding to the topic of psychrophilic FW-AD (19 experimental articles and 3 reviews). From these 22 articles, information on the influence of low temperature on FW-AD, and strategies to improve the FW-AD process under psychrophilic conditions were identified, along with the possible topics for future research.

3. Results and discussion

3.1. Anaerobic digestion of food waste

The consortia of microorganisms that secrete specific enzymes [41] transform the degraded organic fraction of the substrates and convert it into biogas mainly composed of CH4 (50%–80%) and carbon dioxide (CO2) (30%–50%) [19]. The remaining fraction (10%) is converted into digestate, a semi-solid material with great potential use in soil recovery and agricultural activities [19, 42]. Figure 1 shows the stages of the FW-AD process.

Disintegration is the preliminary step of several metabolic stages that make up the AD process [44] and mainly associated with MSW and FW [17]; at this stage, a series of processes, such as lysis, nonenzymatic decomposition, phase separation, and physical decomposition (i.e., FW grinding), occur [45]. The first biochemical stage of AD is hydrolysis, which involves enzymes that mediate the transformation of soluble organic materials and components of greater molecular mass, such as lipids, polysaccharides, proteins, fats, and nucleic acids [25].

Hydrolysis rate is influenced by particle size, substrate composition, the presence of lignin and fibrous compounds that form microfibrils that prevent the degradation of other polymers [43], so the hydrolytic stage is the limiting stage of the process [46, 47]. Hydrolysis also depends on

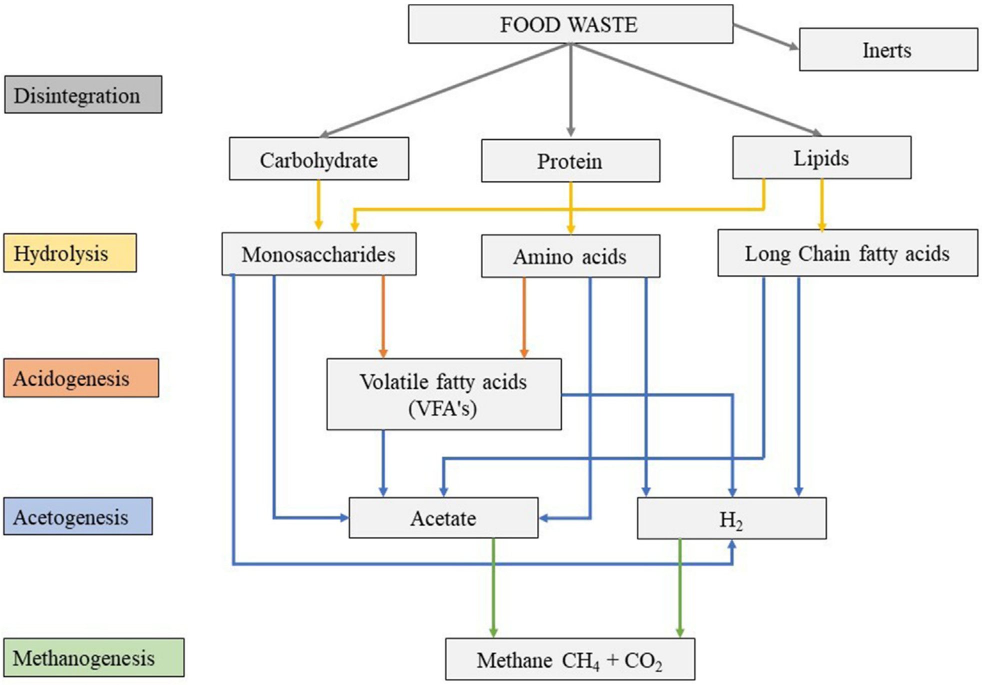

Figure 1. Anaerobic digestion of food waste according to [41, 43].

factors such as process temperature, since when temperature decreases, membrane functions and substrate uptake into the cell of microorganisms are inhibited, which may explain the low rate of hydrolysis under psychrophilic conditions [48, 49, 50].

During acidogenesis stage, monomers resulting from hydrolysis are absorbed by different fermentative and obligatory bacteria and then degraded into short-chain organic acids, such as butyric, propionic, and acetic acids, in addition to hydrogen and CO2 [51]. The conversion of the products of acidogenesis into compounds that form substrates for the production of CH4, acetate, hydrogen and CO2 occurs during acetogenesis. Here, approximately 70% of the digested organic matter is converted into acetic acid, and the remaining fraction is concentrated in the hydrogen formed [25].

In the methanogenic stage, the production of CH4 and CO2 is carried out by methanogenic *archaea* under strict anaerobic conditions [52]. Methanogenesis is a critical stage in the AD process, because it is the slowest biochemical reaction in the AD [25], which can result in the accumulation of VFAs and consequently, inhibition of the methanogenic activity of microorganisms [53].

AD depends on the composition of the FW therefore, their characterization is of interest [3], Campuzano and González-Martínez [54] collected the physical, chemical, elemental, and bromatological characteristics of FW described in studies conducted in Oceania, Asia, North America, and the European Union and attributed the variations of the characteristics of the waste to different cultural lifestyles, systems of waste management, and processing conditions. Carbon, hydrogen, humidity, starch, and volatile solids (VS)/total solid (TS) ratios showed the lowest variations, while total phosphorus, sulfur, hemicellulose, Kjeldahl nitrogen, free sugars, lignin, and raw fiber demonstrated the greatest variations. Table 2 shows the composition of FW reported in several studies and countries.

TS influences the performance of AD, especially in terms of the efficiency of CH4 production [68]. Forster-Carneiro et al. [69] and Abbassi-Guendouz et al. [70] showed that CH4 production decreases as the TS content increases from 10% to 25% and from 20% to 30%; by contrast, Yi et al. [71] concluded that increases in TS content from 5% to 20% lead to higher CH4 yields and a decrease in VS. The difference in these results may be attributed to differences in substrate composition [71].

FW is generally acidic ($pH < 6$) and features high humidity (>70%), C/N ratios between 15 and 36, and phosphorus concentrations of less than 1% [7, 43, 72]. When the C/N ratio is low, levels of free NH3 increase, which inhibits the AD process [73]. By contrast, high C/N ratios indicate nitrogen deficiency for the synthesis of biomass [23].

Carbohydrates are considered the most important organic components for biogas production [74]. However, carbohydrates, have rapid and slow degradation components; the fast degradation constituents has a higher hydrolysis rate, which produces high CH4 yields, and the slow degradation components, in which lignocellulosic material predominates, the hydrolysis of the process is affected, so this is the limiting stage of the FW-AD [15, 75]. High concentrations of carbohydrates could affect the C/N ratio, and increases in organic matter could restrict nutrients and lead to rapid acidification in the AD system [76].

Carbohydrates contain lignocellulose, which is composed of cellulose (35%–50%), hemicellulose (20%–35%), and lignin (10%–25%) [77]. Cellulose is a linear glucose homopolysaccharide with strong β-1,4-glycosidic bonds [78], has microfibrils that containing hydroxylic groups and are linked to each other by hemicellulose and pectin and covered by lignin [79]. This complex structure renders the substrate resistant to chemical and biological degradation [80].

Hemicellulose forms a rigid matrix in lignocellulosic materials, has a lower molecular weight than cellulose, and features less branching [80], making; thus, it is easier to degrade than cellulose [43]. Lignin is considered a component that is challenging to degrade during FW-AD [81]; therefore, microorganisms are unable to use it directly as a substrate [79].

FW also contains lipids, CH4 yields from lipids are higher than those from other organic substances [76]. However, the excessive presence of these compounds in the digester could reduce the hydrolysis rate and result in system failure because lipids could adhere to other compounds, generate long chain fatty acids (LCFAs) and glycerol, and, ultimately, reduce the activity of certain enzymes involved in the AD process [7, 82]. The LCFAs found in FW usually depend on their origin (i.e., animal or plant) [83].

Additionally, the physical characteristics of FW influence the AD process especially on the hydrolysis stage, such particle size and rheological properties (viscosity, consistency index and substrate behavior index), density and humidity [84, 85, 86], being recommendable to analyze the reduction of particle size of FW [87]. Authors such as Mbaye et al. [88], Hreiz et al. [89] and Baroutian et al. [10] indicate that rheological properties could be used as an indicator to monitor biogas production.

In summary, variations in the composition of MSW do not allow the generalization of the characteristics of the wastes [90]. Thus, must be conducted detailed analyses of the physical (e.g., particle size, rheological properties, density, humidity), chemical (e.g. TS, VS, Kjeldahl nitrogen, total phosphorus), and bromatological (e.g., raw fiber, proteins, carbohydrates, lignocellulosic matrix, lipids) characteristics of the

Table 2. Composition of FW reported in several studies.

Country	TS (%)	VS (%)	VS/TS (%)	C/N	pH	Carbohydrates (%)	Protein (%)	Lipids (%)	References
Japan	19.7	95.4	-	-	-	59.8	21.8	15.7	[55]
China	17.2	85	-	-	-	62.7	15.6	18.1	[56]
Korea	18.1	17.1	94	13	6.5	11.2	3.3	2.3	[57]
China	18.3	87.5	-	-	-	35.5	14.4	24.1	[58]
Korea	14.3	98.2	-	-	-	48.3	17.8	-	[59]
Ireland	29.4	28.0	95.0	14	4.1	-	18.1	19	[60]
Greece	18.5	94.1	-	-	-	55.0	16.9	0.96	[61]
China	23.2	21.7	93.5		4.4	13.7	2.9	6.5	[62]
China	20.1	19.2	95.8	28	-	33.2	14.0	25.3	[63]
Colombia	30.6	95.2	-	18,3	4.5	-	-	-	[64]
China	24.3	22.5	92.6	23	5.0	-	3.3	-	[65]
Colombia	29	25.3	87.2	27	-	-	-	-	[66]
China	19.1	-	93.2	14	4.5	12	2.5	3.5	[67]
China	26.2	-	94.8	13	5.2	10	6.3	8.2	[67]
China	12.7	-	95.4	10	5.0	36	41.5	19	[67]

TS: Total solids; VS: Volatile solids; C/N: carbon/nitrogen ratio.

substrate [54], as an essential step in the selection of the most appropriate strategy to improve the FW-AD process and optimize its use [91].

3.1.1. Trends of research on the anaerobic digestion of food waste

The bibliometric analysis identified 272 scientific articles published in the period of 2000–2021: 195 were published in Scopus, 65 in WOS and 12 in SciELO (Figure 2).

The growing trend of research on FW-AD is consistent with the findings of authors such as Chen et al. [37], Lin et al. [20], and Casallas-Ojeda et al. [35]. Research on FW-AD has shown significant growth, especially in the last 12 years, at the international level. The number of publications found in Scielo (Latin American context) on the topic, was greatest in the period of 2014–2021, and the articles obtained represented 5% of the studies found at the international context.

The increase in studies on FW-AD from 2009 may also be associated with the inclusion of new concepts, such as circular or green economies, which promote the reduced generation of waste, reintroduction of waste-generated in production processes, and final disposal, thus contributing to the well-being of the population reducing negative environmental impacts [92, 93]. These concepts are also associated with the fulfillment of sustainable development objectives because they are the commitments and priorities of the international community, specifically in relation to achieving sustainable cities and communities and responsible production and consumption to promote resource and energy efficiency and reduce waste generation through prevention, reduction, use, recycling, and reuse [94].

In terms of geographical location, the countries with the greatest number of publications on FW-AD are China, the United States, India, South Korea, Italy, Japan, the United Kingdom, and Canada. Asian countries, such as China and India, are also at the top of the list because several institutes and nongovernmental organizations have established different types of anaerobic digesters at the domestic and commercial scales for the same purpose [95].

The research approach in China is associated with FW management, especially its treatment and use, indeed, in 2007, 26.5 million biogas plants (10.5 billion m^3 biogas) were built in the country. Biogas production from domestic waste (2 billion m^3), agricultural processing waste (6 billion m^3), animal waste (150 billion m^3), and agricultural waste (90 billion m^3) increased to 248 billion m^3/year in 2010 [96].

In Germany, Spain, and England, FW-AD has been largely implemented at the industrial scale, with a capacity of at least 2500 t/year [95]. The growing trend of research on FW-AD in the United States and the United Kingdom could be attributed to increased interest in improving the management and use of FW [37]. In Latin America, the country with the largest number of publications on this topic is Brazil. Figure 3 shows a map of keywords related to the search equation: the main keywords were labeled in a circle, with each circle's size defining the frequency of appearance of these words in the analyzed articles; the larger is the circle, the greater is the co-occurrence. The color represents the time, and the lines represent the links between keywords. In addition, the distance between two keywords indicates the strength of the relationship; that is, the closer they are, the more connections they have [97].

In the keyword map, variables influencing FW-AD were identified and categorized into three groups (Figure 4).

The number of published articles describing the effects of several variables on FW-AD showed the order Group I: Substrate and environmental variables (65% of the publications) > Group III: Operational parameters (21% of the publications) > Group II: Inoculum (14% of the publications). Given interest in research on approaches to improve FW-AD under psychrophilic conditions and taking into account that this condition is one of the least studied variables.

According to the literature review of AD under psychrophilic conditions with different substrates, 40% of the studies (77 articles) evaluated the process with wastewater sludge, 28% were conducted with wastewater (55 articles), 21% were conducted with manure (41 articles), and only 11% of the studies focused on FW (19 articles). This finding indicates that FW-AD at low temperatures has scarcely been studied. Given that different substrates have different characteristics, FW-AD is not comparable to the conventional AD of substrates such as manure and sewage sludge [98]; thus, the former process should be investigated further [99].

Table 3 shows the conditions of 19 experiments on psychrophilic FW-AD. Most studies were conducted at 20 °C, which, according to the bibliometric analysis, is a temperature that has been mainly used over the

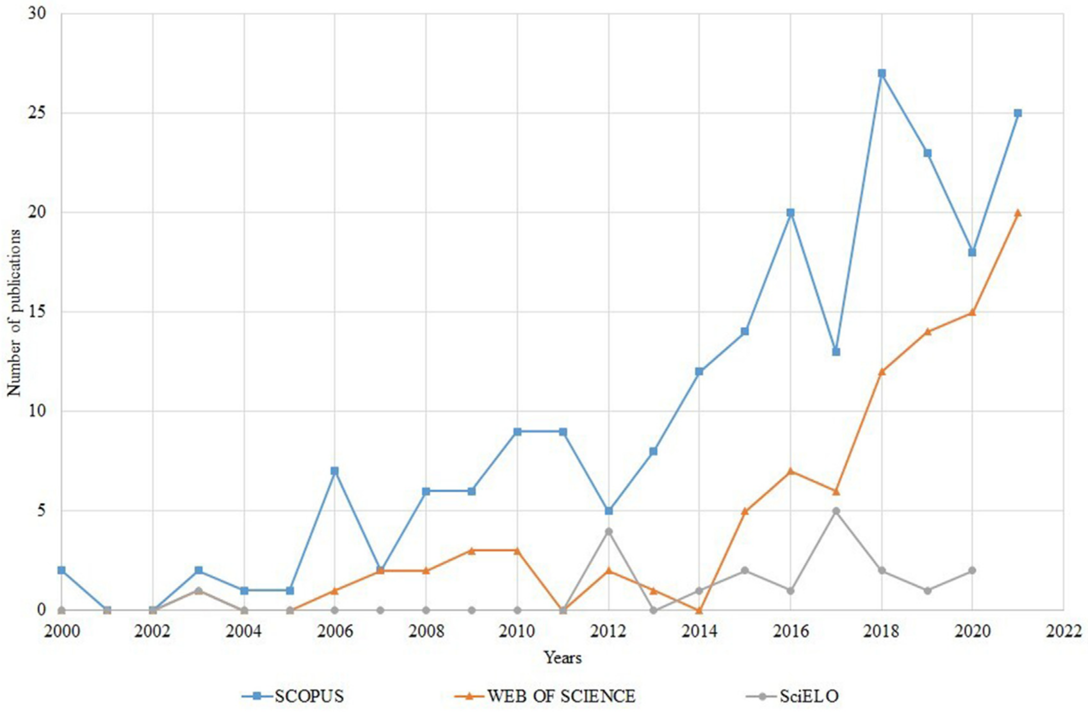

Figure 2. Number of publications on FW-AD published in 2000–2021.

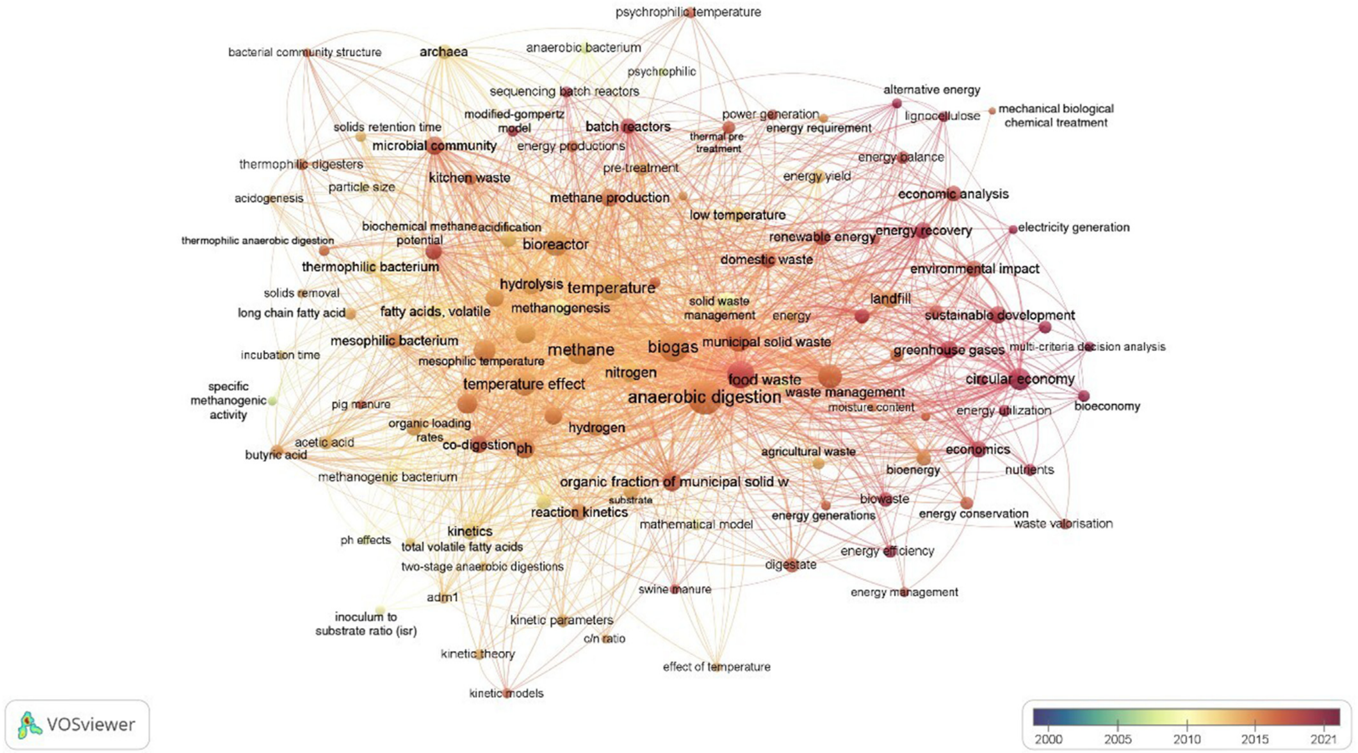

Figure 3. Map of keywords of research related to FW-AD.

last 9 years. The most studied variables (Group I) are those associated with the substrate type and environmental variables (8 publications), including comparisons of the process in the psychrophilic and mesophilic ranges, co-digestion with other substrates, and the digestate.

The second group consists of variables related to the operational parameters (7 publications); these variables included the organic load rate, bioelectrochemical AD, head space, kinetic models, and the reactor scale. Finally, the third group consists of variables related to the

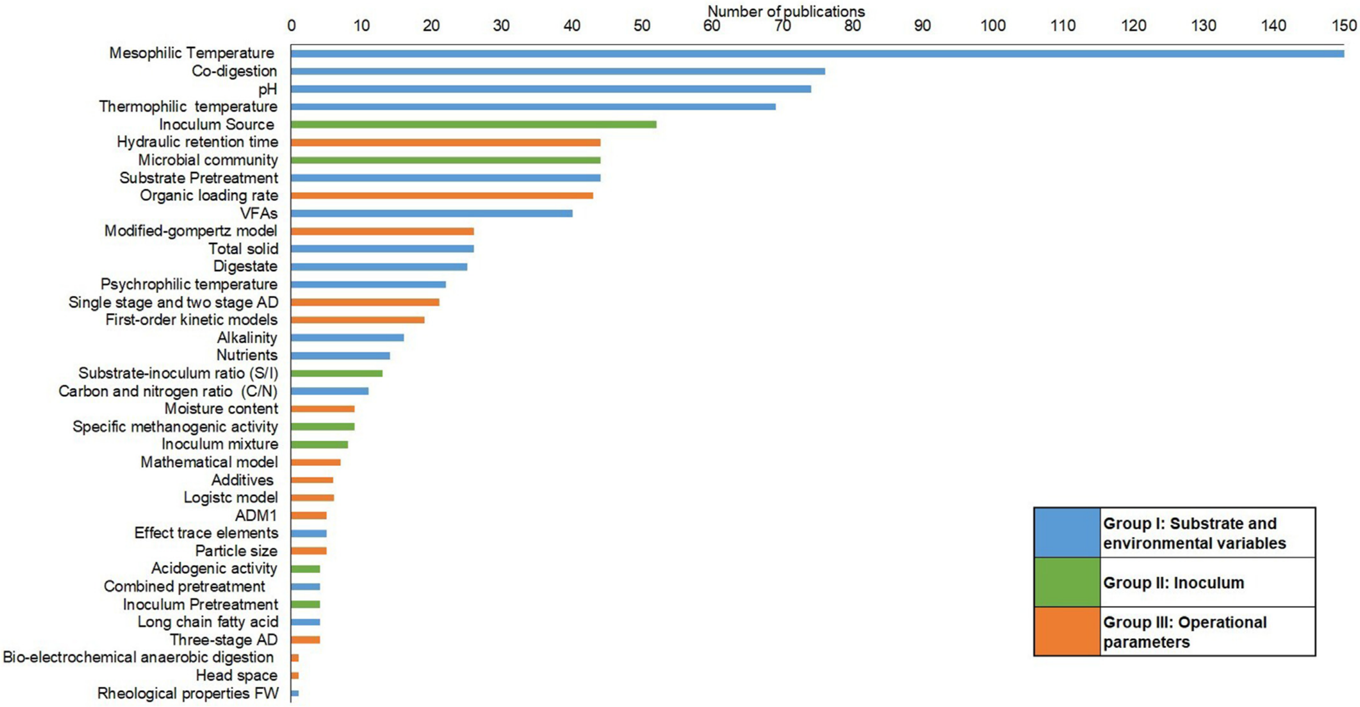

Figure 4. Number of articles on variables influencing FW-AD.

Table 3. Summary of experiments on FW-AD under psychrophilic conditions.

Substrate	Inoculum	Operating conditions	T°C	Research objective	Countries	CH4	Units	% CH4	Reference
FVF	Sludge from a mesophilic digester	Anaerobic tubular digester; laboratory scale; TS: 4%, 6%	20	Temperature; psychrophilic, mesophilic, and thermophilic comparison	Tunis	TS 4%: 224.05 TS 6%: 350.00	mL CH4/g SV	TS 4%: 58 TS 6%: 56	[100]
OFMSW	Anaerobic sludge	Batch, 2 L	25	Temperature; psychrophilic, mesophilic, and thermophilic comparison	China	-		65.2	[101]
FW, landscape waste	Wastewater and manure mixed with FW	Pilot-scale anaerobic digester	25	Design and testing of a pilot laboratory scale psychrophilic anaerobic digester; energy and electricity potential of FW	Lebanon	23	L/week	65	[102]
MSW	-	-	20	Hydraulic retention time (HRT); cost	UK	380	mL CH4/g SV	-	[103]
FW	Seed sludge	Batch, 400 mL	15	ISR ratio	India	730	mL/g DQO	-	[104]
FW	Sludge from a pilot-scale digester	Sequencing batch reactor	20	Optimal operating conditions (e.g., OLR, HRT, cycle length)	Canada	401	mL CH4/g SV	64–69	[29]
FW	Cow dung	Batch reactors operated in parallel, small scale, 872 L	25	Temperature effect	Thailand	12	L/day	58	[105]
FW	Sludge from a laboratory scale psychrophilic (20 °C) digester	Sequencing batch reactor - PBEAD	20	Methane production; changes in *archaeal* communities - PBEAD	Korea	270	ml CH4/g DQO	-	[106]
Paunch (Cellulose, hemicellulose)	Seed sludge mesophilic	Sequential leach bed reactor - laboratory scale	22	Temperature effect	Canada	148.3	mL CH4/g SV	-	[107]
FVF	Cow rumen	Full-scale anaerobic digester	18.2 16.9 14.1 16.8	Development and implementation of low-cost AD technologies to treat OMSW	Bolivia	18.2 °C: 120 16.9 °C:111 14.1 °C:120 16.8 °C: 150	mL CH4/g SV	43%	[108]
FVF	-	Batch, 10 L	20	Temperature effect; co-digestion	China	22.17	mL CH4/g SV	23	[109]
FW	-	Anaerobic ceramic membrane bioreactor, laboratory scale, 24 L	20	Effects of temperature, filtration performance, microbial community structure	South Korea	100	mL CH4/g SV	-	[110]
FW	Sludge biogas plant (pig manure)	Batch, 5 L	20	ISR ratio (1.5 y 0.5) OLR (1–3 g SV/L)	Chile	ISR (1.5) = 53.2 ISR (0.5) = 163 (1 g SV/L) = 117 (2 g SV/L) = 86 (3g SV/L) = 59	mL CH4/g SV	- -	[111]

(*continued on next page*)

Table 3 (*continued*)

Substrate	Inoculum	Operating conditions	T°C	Research objective	Countries	CH4	Units	% CH4	Reference
FW	Sludge psychrophilic biogas plant (pig manure)	5 L Batch reactors	18	Temperature effect and digestate post-treatment	Chile	63	mL CH4/g SV	55	[112]
FW	Cow dung	Cylindrical reactor (3000 L)	27–15	Single-phase AD; temperature effect (mesophilic and thermophilic conditions); microbial communities	India	418.3 a 13.9 (54.8% reduction during winter vs. summer)	mL CH4/g SV	58.9	[99]
Tea leaf litter, forest tree leaf litter, kitchen waste, locally available plant weeds, cow dung	-	Batch	20	Various capacities and types of reactors using different materials and biomass mixing techniques	India	-		45–50	[113]
FW	Mixture of flocculent sludge and granular sludge (75/25)	Batch, 250 mL	20	Temperature; psychrophilic, mesophilic, and thermophilic comparison, Head space	Colombia	47.96	mL CH4/g SV	-	[114]
FW	Sludge from the first stage of a mesophilic biogas plant (40 °C)	Semi-continuous two-stage reactor with (V = 270 L)	21	Two-stage psychrophilic FW-AD; comparison with the conventional single-stage mesophilic process	Czech Republic	444	mL CH4/g SV	-	[115]
FW and sewage sludge	Anaerobic sludge	Batch, 300 mL	20	Impacts of different organic loads	Iran	164	mL CH4/g SV	66 ± 5	[116]

FVF: Fruit and vegetable waste; FW: Food waste; OFMSW: Organic fraction municipal solid waste; MSW: Municipal Solid Waste; ISR: Inoculum substrate ratio; PBEAD: Psychrophilic bioelectrochemical anaerobic digestion OW: Organic waste.

Table 4. Advantages and disadvantages of FW-AD under different temperature conditions.

Range	Advantages	Limitations	Ref.
Psychrophilic	• The most appropriate option for regions with cold and temperate climates. • Shows great economic advantages on account of its low operating cost because it does not require digester heating. Hence, its energy demand is low. • Some studies show that psychrophilic anaerobic digesters can successfully degrade organic matter. • Psychrophilic microorganisms can withstand higher concentrations of inhibitory compounds compared to mesophilic or thermophilic bacteria. • At low temperatures, ammonium does not cause failure of the digester.	• The reduction of organic matter, the efficiency of the process, the rates of substrate utilization and bacterial growth decrease, which leads to reductions in CH4 production. Additionally, the elevated solubility of CH4 at low temperatures results in lower concentrations of the compound in the gas phase. • The lower growth rate of anaerobic bacteria makes the digester to operate with longer solids retention times, approximately twice as long as AD under mesophilic conditions. This results in a larger size in the digester. • The hydrolysis rate decreases at low temperatures, leading to the accumulation of non- or partially degraded organic substrates in the sludge bed of the reactor. • There is a gap in the literature on the use of psychrophilic microorganisms isolated from permanently cold habitats as inoculum in the AD process. The exclusive use of mesophilic microorganisms acclimated to low temperatures generates a drecrease in the methanogenesis rate. • Microorganisms may have problems with assimilate hydrogen. • A decrease in temperature inactivates methanogenic microorganisms by reductions in the fluidity of the membrane render it biologically inactive, increases its viscosity, and causes the hardening of transport proteins incorporated in the membrane. Therefore, the transport of the substrate through the cell membrane is inhibited. • A decrease in temperature could affect the stability of microorganisms; cause changes in pH and decrease CH4 production. • A fraction of the biogas is solubilized in the digestate; therefore, the digestate contains organic matter that is converted into NH3 and CH4, which translates into a loss of energy efficiency and greater environmental impacts.	[24, 29, 30, 42, 48, 103, 107, 111, 115, 117, 126, 130, 140, 141, 142, 143, 144, 145, 146]
Mesophilic	• Offers greater process stability and bacterial richness and requires lower energy costs compared with AD under psychrophilic and thermophilic conditions. • Has low risk of inhibition by ammonium and LCFAs. • Has higher removal rates for chemical oxygen demand and total volatile solids.	• Nutrient imbalance may occur. • In cold climatic conditions, reactor heating is required to reach mesophilic temperature, which leads to higher energy consumption and higher costs for implementation.	[7, 21, 147, 148, 149, 150, 151]
Thermophilic	• Leads to higher metabolic, reaction, and hydrolysis rates, shortens the hydrolytic and methanogenic phases, and generates higher CH4 yields. • Has higher pathogen destruction rates. The digestate obtained under this condition contains lower amounts of pathogens and, thus, is more suitable for agricultural use. • Has lower contents of hydrogen sulfide in the biogas, shorter retention times, lower reactor volume demands, and higher degradation rates of organic matter compared with other methods.	•Affects biogas yields on account of the production of other volatile gases, such as NH3, which affects methanogenic activity. • Thermophilic methanogenic microorganisms are sensitive to temperature fluctuations. • Thermophilic conditions tend to accumulate propionic acid, which generates acidification during the AD process and inhibits the production of biogas. • External energy is required to maintain the desired temperature. • Some studies suggest that thermophilic FW-AD requires more trace elements than mesophilic FW-AD.	[48, 73, 92, 100, 150, 152, 153, 154]

inoculum (4 publications) and discussed topics such as the analysis of the structure of the microbial community and the substrate/inoculum relationship.

The majority of the studies included in the bibliometric analysis, were conducted at the laboratory scale. The batch reactor most often used had volumes of 0.25–3000 L. Biochemical CH4 potential (BMP) investigations were the major type of study conducted, followed by tubular digesters and semi-continuous reactors. Most studies observed CH4 generation, which means FW-AD under psychrophilic conditions is a viable option for some regions. Maximizing the efficiency of FW-AD at low temperature conditions is recommended.

3.2. *Psychrophilic anaerobic digestion of food waste*

The effects of low temperature on CH4 generation have been investigated in natural psychrophilic environments [117, 118]; in general, under psychrophilic conditions the Archaea of the genus Methanothrix, which consume only acetate and not hydrogen, are dominant over Methanosarcina, which consumes both acetate and hydrogen and carbon dioxide [119, 120]; according to authors such as Conrad [121] and Nozhevnikova et al. [122], when the AD temperature is reduced, acetoclastic methanogens increase by about 85% and hydrogenotrophic methanogenesis is minimal, supporting the claim that acetoclastic

Table 5. Strategies and research trends of Group I: Substrates and environmental variables.

Strategies to improve FW-AD	Research trends for future studies	Reference
• Measurement of the rheological characteristics of the substrate: Investigation of changes in characteristics, such as dynamic viscosity and limit viscosity. • Reduction of substrate viscosity: Addition of enzymes to reduce the substrate viscosity in the digester.	• Information on the methods of measuring rheological properties (e.g., viscosity) in the substrate (e.g., FW) is limited and should be further investigated. • The use of enzymes to reduce viscosity requires more research because cost and selectivity are the main drawbacks of the application of enzymes. • Studies on the relationship between temperature, different particle sizes, the concentration of TS and VS, density and humidity are necessary to understand the rheological properties and influence of mechanical pretreatments on the rheological properties of FW. • Application of rheological mathematical models, such as the Herschel–Bulkley, Ostwald, and Bingham models.	[24, 86, 155]
• Bioaugmentation	• Methane production could be increased by bioaugmentation, selecting strains of psychrophilic bacteria that can enhance their number and microbial activity.	[119]
• Co-digestion of substrates: Application of mixtures of two or more substrates could increase the yield of CH4; this strategy is the focus of the most recent research and has a positive effect on the buffer capacity of the process. • Some possible co-substrates include crop residues and different parts of plants, certain strains of bacteria or fungi, microbial consortia, enzymes obtained through bioaugmentation, manure from animals such as flames, pigs and cows, and chemical additives such as adsorbents (e.g., pectin, activated carbon, silica gel, kaolin, bentonite, gelatin, polyvinyl alcohol).	• The use of nanoparticles to add micronutrients may promote microbial growth in AD; however, their exact effects on the FW-AD process have not been investigated, and environmental and economic effects remain a concern. • The choice of the appropriate mixing ratio is an important parameter in co-digestion that should be optimized.	[33, 92, 130, 156]

methanogenesis is more thermodynamically favored than hydrogenotrophic methanogenesis under low temperature conditions [119, 123].

Dev et al. [24] and Feller [124] indicated that some psychrophilic microorganisms can grow even at subzero temperatures and carry out active methanization through evolutionary mechanisms to address the thermodynamic restrictions that accompany them. Microorganisms may be strict and facultative psychrotrophic; both types of organisms can grow at 0 °C, but the former has an optimal temperature of $<$15 °C and a maximum temperature of 20 °C whereas the latter has an optimal temperature of $>$20 °C [30, 33]. Both types of microorganisms can be isolated under psychrophilic conditions with operating temperatures between 15 and 20 °C [33, 125, 126].

In the case of reactors operated at low temperatures, characterization of the methanogenic population has been related to the performance of the reactor [127, 128]. Little research on the activity of obligate psychrophilic microorganisms is available, and most of the literature suggests increasing the operating temperature of bioreactors to the mesophilic range to improve biogas production [129].

Jaimes-Estévez et al. [130] evaluated the AD of manure at 12 °C in a tubular digester that had been in operation for 8 years, microbiological analysis revealed a diverse population that had adapted to the conditions of AD; the process provided a selective environment that was favorable to the methanogenic *archaea* communities; by contrast, bacterial communities decreased over the course of AD. Park et al. [106] evaluated the characteristics of FW-AD at 19.8 °C in a bioelectrochemical anaerobic digester with an electrode, and the results showed that the main families of microorganisms present in the stabilized sludge that proliferate under low temperatures belong to the families Pseudomonaceae, Methylophilaceae, Sphingobacteriaceae, and Coriobacteriaceae, among others.

Choudhary et al. [99] evaluated biogas production from FW in a reactor with temperature variations (5–27 °C) and found that the resulting microbial community shows a wide phylogenetic diversity of hydrolytic and methanogenic populations.

The decrease in temperature affects the physical variables (particle size, rheological properties such as viscosity, consistency index and flow behavior index, TS and VS, density, and humidity) of the FW and inoculum (viscosity increases) and reactor liquid mixture [119]. The increase of viscosity affects the mixing of the substrate with the inoculum, reducing the diffusion of soluble substrates and limiting the mass transfer, resulting in a reduction of affinity of microorganisms for the substrate. All this causes shortcomings in the kinetics of the process and generates a slow hydrolysis rate with a longer duration of the lag phase and low CH4 yields [24, 112, 120].

The psychrophilic temperature also affects some chemical variables of FW-AD, the study by Wang et al. [131] found that low temperatures have a negative effect on the efficiency of VFAs production in the acidogenic phase, at 35 °C the total VFAs content was 4403 mg/L and the acetic acid content was 77% of total VFAs, while at 20 °C the total VFAs content decreased to 1270 mg/L and the acetic acid content accounted for only 65% of total VFAs; the content of butyric acid and valeric acid remained stable at 35 and 20 °C. The pH is also reduced under low temperature conditions, because CO2 solubility increases [132, 133]. Boullagui et al. [100] found that AD under psychrophilic conditions of fruit and vegetable wastes was completely stopped due to the accumulation of VFAs and the decrease of pH.

Temperature also influences NH3 content [134] at high temperatures NH3 increases and can produce inhibition [135], while under psychrophilic conditions NH3 concentration is reduced [136]. In the study of Massé et al. [137] the final NH3 concentration in the reactors was 108 mg/L at 20 °C and 304 mg/L at 35 °C, results in agreement with King et al. [118] and Ortner et al. [138] who state that AD under low temperature conditions is efficient in minimizing NH3 content compared to mesophilic and thermophilic systems. In addition total chemical oxygen demand (COD), as well as solids removal, are minimally affected by the low temperature [139].

Compared with psychrophilic AD without active heating, mesophilic and thermophilic AD have been better studied and widely applied [24, 29, 33]. Bouallagui et al. [100] studied the effect of temperature on CH4 production from fruit and vegetable residues and found that the production of CH4 under psychrophilic, mesophilic, and thermophilic conditions was 350, 451.77, and 608.44 mL CH4/g VS, respectively. Casallas-Ojeda et al. [114] analyzed the simultaneous influence of head space (20%, 35%, and 50%) and temperature (20, 35, and 55 °C) on the BMP of FW and obtained production rates of 47.96 mL CH4/g VS in the psychrophilic group, 81.47 mL CH4/g VS in the mesophilic group,

Table 6. Strategies and research trends for Group II: Inoculum.

Strategies	Research trends for future studies	Reference
• The use of inocula obtained directly from cold regions with psychrophilic methanogenic communities could increase the production of biogas at low temperatures by providing greater psychrophilic activity during methanogenesis. • Acclimatization of mesophilic inocula at low temperatures could be attempted, taking into account that the most appropriate inoculum is the one that is acclimatized under the same conditions under which the AD process will be operated.	• The performance of psychrophilic microorganisms in FW-AD under low temperature conditions could be evaluated. • Further research is needed to develop a psychrophilic inoculum directly from cold regions. • Studies on the effect of the use of mesophilic and psychrophilic inocula for FW-AD under temperatures below 20 °C are lacking. • Studies on the effect of substrate concentration and lipid, protein, and carotenoid contents could support the growth of the microbial population under psychrophilic conditions. • Studies on how to increase the membrane fluidity of microorganisms are necessary.	[24, 30, 33, 107, 126, 129, 148]
• Stimulation of the growth of psychrophilic microorganisms via the addition of alcohols and the use of specialized enzymes, such as trehalose disaccharide, which allows the microorganisms to acclimate to low temperatures and protects them from freezing, desiccation and hyperosmolality.	• Studies evaluating the effect of the addition of alcohols and specialized enzymes to the inoculum used in the FW-AD process could be conducted to identify their effect on the microbial community and production of CH4.	[24, 161, 162, 163]
• Studies show that methanol increases the amount of methanobacterial and methanobacterial hydrogenotrophic methanogens and increased the production of CH4 at low temperatures. Methanol also promotes the growth and methanogenesis of *Methanolobus psychrophilus* at 18 °C.		
• Understanding microbial communities through taxonomic analysis and the application of high-throughput sequencing technology in domestic digesters in cold climates to determine the broad and complex interactions of microbial communities within their environments and hosts.	• Taxonomic analysis could be conducted and high-throughput sequencing technology could be applied to the inoculum to achieve greater compression of the microbial community.	[117, 130, 164]
• Addition of coagulants to the inoculum could improve its characteristics.	• Addition of coagulants improves sludge settlement but can inhibit microorganisms; hence, the optimal concentration to be added should be studied. Moreover, the behavior will vary depending on the type of coagulant used. Therefore, each case should be evaluated prior to application.	[35, 165]
• Addition of macronutrients and trace elements in the inoculum by using a co-substrate.	• The literature on methods to improve the quality of the inoculum by conditioning to enhance its characteristics and maximize the production of CH4 is scarce. This topic could be studied further.	[165]
• Leaving the inoculum at the temperature at which the process will be developed to achieve a thermal acclimatization period and a shorter adaptive phase, thus avoiding low CH4 production once the reactor is operated.	• Studies with unacclimatized and acclimatized sludge to analyze the influence on methane generation. -	[35, 166, 167]
• Rheological properties	• Rheological properties have mostly been studied in activated sludge, but there are few studies that delve into the rheological properties of anaerobic sludge. • The decrease in temperature results in an increase in sludge viscosity, which hinders mixing with FW and could affect methane production, for this reason it is important to rheologically characterize the inoculums.	[86, 155, 177]

and 107.06 mL CH4/g VS in the thermophilic group. Table 4 shows some advantages and limitations of each temperature range in FW-AD.

4. Strategies to improve the anaerobic digestion of food waste under psychrophilic conditions and future research trends

The bibliometric analysis revealed possible improvement strategies for FW-AD at low temperatures, which encompass a set of actions that could be implemented to improve the process and were categorized according to the previously defined groups. Research trends reflecting possible topics for future research emerged from these strategies:

4.1. Group I: substrates and environmental variables

An important research trends shown in Table 5 is the temperature influence on the rheological properties of FW, so far no consensus has been reached regarding the specific role of substrate rheology in biogas production [10]. Guanoluisa [157] and Miryahyaei et al. [144] reported that rheological properties could be used as an indicator to monitor biogas production, so performing studies on the interaction between substrate degradability, temperature, physicochemical variables and substrate rheology is a topic of interest [10]. Table 5 also shows that the performance of FW-AD can be improved by bioaugmentation of some selected strains of psychrophiles which can reinforce the number and activity of functional bacteria [119, 159]. However, there are still limitations that prevent further scale-up of the bioaugmentation technology; some are the selection of the appropriate mixture of microbial cultures, cost, and storage and transportation of the bioaugmentation culture [119]. Finally, although co-digestion is an improvement strategy for all temperature ranges of AD, it could be a way to increase biogas production under psychrophilic conditions [160].

4.2. Group II: inoculum

Table 6 shows that the research trend is focused on using psychrophilic inoculums, because research on low temperature AD for CH4 production has been carried out mainly with mesophilic inoculum acclimated to low temperatures [30, 33]. The use of mesophilic inoculum exclusively is a major issue for FW-AD under psychrophilic conditions because these organisms decrease the rate of methanogenesis [148]. According to Feller [124], only microorganisms adapted to psychrophilic conditions can handle the limitations that occur at temperatures below 20 °C. These adapted microorganisms possess physiological conditions suitable for cold environments, due to the characteristics of their cell membranes in terms of proteins, lipids and enzymes, which makes the microorganisms remain active in psychrophilic environments and show excellent genetic responses to thermal changes [130, 145, 168]. In this sense, psychrophilic microorganisms render AD possible in cold regions and could overcome thermodynamic constraints at low temperatures [133, 169].

4.3. Group III: operational parameters

The most commonly used alternative to improve AD under psychrophilic conditions is to increase the digester temperature [133], however maintaining a high digester temperature is a costly affair [119]. Table 7

Table 7. Strategies and research trends for Group III: Operational parameters.

Strategies	Research trends for future studies	Reference
• Apply new reactor designs and configurations	• Studies on the applications of biodigesters coupled to bioelectrodes, fluidized bed bioreactors, membrane bioreactors, and tubular digesters are necessary to eliminate the issues associated with operation at low temperatures. • Use of hybrid reactors has also been proposed and is an option that could be further explored to optimize the process at low temperatures • Application of a two-stage system: Such a system could promote the generation of CH4, thereby increasing the efficiency of methanogenic microorganisms.	[30, 80, 115, 119, 170, 171]
• Operation with a high solid retention time (SRT) and low organic loading rate to maintain the population of acetoclastic methanogenic microorganisms, which are responsible for CH**4** production under psychrophilic conditions. • Increasing the SRT results in a larger biodigester size; a decrease in operating temperature requires an increase in HRT from 30 days to 50 days to maintain efficient biogas production..Operation at the S/I ratio suitable for low temperature conditions	• The incidence of SRT and the rate of organic loading on the efficiency of the process under psychrophilic conditions FW-AD could be examined. • Studies with large-scale digesters and economic cost analysis could be conducted to provide a solid basis for the practical applications of FW-AD under psychrophilic conditions. • Studies to evaluate different S/I ratios under low temperature conditions.	[24, 130]
• The use of passive solar heating design (e.g., solar radiation gains, insulation, and greenhouse). Artificial heating can be achieved with wind energy or by using liquid fuels. The digester could also be insulated with polymeric materials.	• Study various alternative heat sources, such as using digester biogas for heating	[108, 171]
• Application of kinetic models: This strategy would help establish the influence of different variables of the FW-AD, as the effect of temperature on FW-AD. The use of several models is recommended to identify the one that best adapts to production trends.	• The literature on kinetic and mathematical models for FW-AD in psychrophilic temperatures is limited; thus, more research on this topic is required.	[35, 99, 172, 173]
• Evaluating different S/I ratios	• The S/I ratio has been little studied in psychrophilic conditions, so it should be further investigated. it	[176]
• Evaluate simultaneously the variables related to FW-AD under psychrophilic conditions	• There are few studies that simultaneously evaluate variables related to FW-AD under psychrophilic conditions, so it is important to know how the interaction of all variables affects the process of biogas production.	[35, 132]
• Rheological properties of the inoculum-FW mixture	• The amount of substrate and inoculum added to the reactor generates changes in the rheological properties of the mixture, so characterizing the mixture under different conditions of S/I ratios is an aspect to investigate that takes on greater importance in psychrophilic conditions where the rheological properties are more affected.	[158, 175, 176]

shows other improvement strategies and trends for future research that do not require heating, one of the most important is reactor design, because it can help increase the efficiency of methane production at low temperature [133].

Studies such as those of McKeown et al. [174], Park et al. [106] and Rusin et al. [115] demonstrate that two-stage system, bioelectrochemical and hybrid reactors can accelerate the production of methane, however very little information on FW-AD by apply new reactor designs and configurations is available in the literature; thus, more research on this topic is required [115, 119]. Another important variable is the S/I ratio, which has been little studied in psychrophilic conditions and depending on the characteristics of the substrate and the inoculum used, the ratio changes [176] hence the importance of evaluating it. Another variable that changes under psychrophilic conditions is the SRT, in this temperature is higher and this represents a larger digester size [130], it is therefore necessary to carry out studies with different reactor volumes to optimize the FW-AD process [33].

5. Conclusions

Temperature is a variable with a great influence on the FW-AD process. Psychrophilic conditions generally demonstrate good applicability to regions with cold and temperate climates; however, under these conditions, the AD process presents limitations in kinetics (e.g., hydrolysis rate, latency phase, microbial activity, and CH4 generation), which decreases the overall efficiency of the process. Thus, identifying and evaluating possible improvement strategies is a necessary undertaking.

Several strategies could improve the performance of FW-AD under psychrophilic conditions; some of these strategies are related to the substrate and environmental variables such as measurement of the rheological characteristics and reduction of substrate viscosity, bioaugmentation and co-digestion. Others are related to the use of inocula with psychrophilic methanogenic communities and others are related to the modification of the configurations and performance of the reactor and operation with a high solid retention time. However, these variables have scarcely been studied in the context of psychrophilic conditions. Thus, future research should focus on evaluating the influence of these variables on FW-AD under psychrophilic conditions.

Declarations

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

Funding statement

This work was supported by Dirección General de Investigaciones of Universidad Santiago de Cali [Project No. 820-621120-1587; CallsNo. 01–2021 and No 01-2022], Universidad del Valle [Project No. CI-21118].

Lina Mariana Rodríguez-Jiménez was supported by Ministerio de Ciencia, Tecnología e Innovación Colombia [Bicentennial Scholarships – Court 1–2020].

Data availability statement

Data included in article/supp. material/referenced in article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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