Frontiers in Environmental Science

TYPE Systematic Review
PUBLISHED 13 February 2023
DOI 10.3389/fenvs.2023.1116053

OPEN ACCESS

EDITED BY
Santiago Septien Stringel,
University of KwaZulu-Natal, South Africa

REVIEWED BY
Nikhil Gauravarapu Navlur,
Dr. B. R. Ambedkar National Institute of Technology Jalandhar, India
Brian Hawkins,
Duke University, United States

*CORRESPONDENCE
M. Fabrizio Ortiz-Sánchez,
✉ mfabrizio.ortiz@gmail.com

SPECIALTY SECTION
This article was submitted to Water and Wastewater Management,
a section of the journal
Frontiers in Environmental Science

RECEIVED 05 December 2022
ACCEPTED 23 January 2023
PUBLISHED 13 February 2023

CITATION
Ortiz-Sánchez MF and Cuevas-Rodriguez G (2023), Energy recovery from wastewater in Mexico: A systematic review.
Front. Environ. Sci. 11:1116053.
doi: 10.3389/fenvs.2023.1116053

Energy recovery from wastewater in Mexico: A systematic review

M. Fabrizio Ortiz-Sánchez[1]* and Germán Cuevas-Rodriguez[2]

[1]Consultant, Guanajuato, México, [2]Department of Civil and Environmental Engineering, Engineering Division, Guanajuato Campus, Guanajuato University, Guanajuato, México

The usage of fossil fuels to generate energy and the lack of wastewater treatment in Mexico are two issues that can be addressed at the same time while developing wastewater treatment technologies that incorporate energy recovery in their process train. We carried out a systematic review based on the PRISMA methodology to identify and review studies regarding energy recovery using wastewater as a substrate in Mexico. Peer-reviewed papers were identified through Scopus, Web of Knowledge, and Google Scholar, using a timeframe of 22 years that represented from 2000 to 2022. After applying the selection criteria, we identified 31 studies to be included in the final review, starting from 2007. The kind of energy product, type of technology used, substrate wastewater, amount of energy produced, and main parameters for the operation of the technology were extracted from the papers. The results show that methane is the most researched energy recovery product from wastewater, followed by hydrogen and electricity, and the technology used to archive it is an up-flow anaerobic sludge bed (UASB) reactor to produce methane and hydrogen. In addition, microbial fuel cells (MFCs) were preferred to produce electricity. According to our data, more energy per kgCOD removed could be obtained with methane-recovering technologies in the Mexican peer-reviewed studies compared with hydrogen recovery and electricity production.

KEYWORDS

energy recovery, wastewater treatment, Mexico, methane, hydrogen

1 Introduction

The environmental impacts of fossil fuels are particularly evident for developing countries (Solarin, 2020), especially those whose economies and energy production rely on them significantly. Mexico is very rich in petroleum, which affects how energy is produced. Fossil fuels represent around 85% of the energy generated to meet energetic demands (Masera and Sacramento, 2022). Mexican crude oil reserves are decreasing for a country that depends so heavily on fossil fuels (Martínez Hernández and Aguilar, 2021). Deforestation, landscape changes, hazardous atmospheric emissions, and effluents that pollute water and soil and destroy biodiversity are just a few of those already known environmental impacts of the mismanagement of the oil industry (Rico et al., 2007). The current governmental administration has not been clear about the future of renewable energies in the country, whereas the actions around the investment extraction and exploitation of oil and gas have been vigorous (Catalán, 2020). Since 2015, Mexico confirmed its willingness to meet the compromises of the 2030 Agenda from the United Nations (SRE, 2019). Thus, clean energy usage in Mexico should be encouraged to mitigate the greenhouse gas emissions used in energy production.

Water and energy demands in Mexico continue to grow despite the slowing of population growth. Nearly 50% of the wastewater produced in Mexico is discharged into the environment with no treatment whatsoever (CONAGUA, 2019); hence, there is a need to develop and install wastewater treatment technologies to achieve a cleaner future. In addition to having the capacity to clean wastewater from pollutants, wastewater treatment processes have the potential to be used to harvest energy and other value-added products, which bring with them environmental and economic advantages (Zarei, 2020). The potential of the country to recover energy from wastewater is astronomical and should be taken into account when installing new technology because it tackles one of the biggest general environmental problems in the country. For instance, several large-scale successful cases have been reported throughout Mexico generating renewable energy while treating wastewater (Ramírez-Higareda et al., 2019). Furthermore, Mexico is an upper-middle-class country (The World Bank, 2023), a member of the North American Free Trade Agreement (NAFTA), the Organization for Economic Cooperation and Development (OCDE), and the G20, where there is an opportunity to implement technologies to recover energy.

Using wastewater as an alternative energy source can mitigate certain environmental impacts and cover certain of the country's energy demands, although it would represent a minimal part of them when compared to fossil fuel energy generation and other alternative energy sources currently operating. Furthermore, Mexico is a country full of resources that are suitable for the task of providing alternative energy sources like biomass, hydroelectric power, wave energy from the oceans, 11,122 km of shores (INEGI, 2020), and photovoltaic energy. In terms of solar irradiation, the country has an annual average of 5.3 kWh/m^2 per day (CONAGUA-JICA, 2012). Nonetheless, the development of these particular technologies also addresses, at the same time, in addition to the issue of energy production without the use of fossil fuels, the possibility of attacking the transcendental problem of discharging untreated wastewater into the environment.

The development of technology capable of recovering energy from wastewater is vital in a country like Mexico, which faces the sanitation and energy supply problems mentioned earlier. Thereby, to advance in the development of technology, there is a need to have a more general perspective of the state of the question regarding the relationship between wastewater treatment, energy recovery, and technology development.

This report aimed to conduct a systematic review of the state of the question of studies about the energy recovery processes for wastewater being developed within the boundaries of the Mexican state and compare the energy recuperation results. All of the aforementioned goals are defined within the selected data sources. To get to the goal of this review, we used the following questions as a guide:

Which technologies are being developed the most?
What is the energy performance of the technologies developed?
What are trends in technology development?
Are there any knowledge or research gaps? If so, what are they?

This review focused on how much energy can be recovered from wastewater producing methane, hydrogen, and electricity, which are the most prominent methods used to recover energy from wastewater.

2 Methods

To achieve this study's goals, the authors conducted a systematic review following the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) (Page et al., 2021) guidelines. This methodology has been successfully right applied when dealing with subjects around and about wastewater and wastewater treatment (Lorick et al., 2020; Agyekum et al., 2022; Emenekwe et al., 2022; Muzioreva et al., 2022).

TABLE 1 Eligibility criteria for studies to be included in this work.

Eligibility criteria	
Document type	Peer-reviewed
Timeframe	2000–2022
Language	English and Spanish
Country	Mexico
Data type	Quantitative
Study focus	Energy recovery from wastewater

2.1 Eligibility criteria

For the studies to be included in this review they had to meet the eligibility and exclusion criteria considered in Table 1 and Table 2. We focused on studies that explore methods and technologies that recover energy from wastewater and wastewater byproducts in Mexico.

Only articles focused on energy recovery using wastewater were taken into account. Energy recovery using byproducts from wastewater treatment or co-digestion process were discarded. Co-digestion was not explored in this work in order to explore research specifically on wastewater treatment and energy generation with the aim of promoting technological development in this area in which there is a lack of work to be done. Only peer-reviewed scientific articles focused on wastewater and energy recovery were taken into consideration. Additionally, all grey literature, technical reports, conference papers, reviews, news, and thesis were rejected from this study. We took only into consideration the papers within the timespan of 2000–2022. This work included works written in English and Spanish, and studies in another language were rejected. Regarding document type, only peer-reviewed studies that assess research carried on in Mexico or with Mexican wastewater were included in this study. Publications regarding a bigger region, such as Latin America or Global South were excluded from this work. The term "wastewater" in this work includes industrial and domestic wastewater.

2.2 Data sources and search strategy

Two databases of journals and one search engine were used: Scopus, Web of Science, and Google Scholar, respectively. The latter was used to identify peer-reviewed studies in Spanish because the majority of the most important databases in Mexico and Latin America (e.g., Redalcyt and Dialnet) lack an advanced search component. The search of studies was defined by search strings shown in Table 3.

In the two databases of journals and one search engine, the search string was refined using only the "Article" document type. For Scopus and Web of Science, the timeframe was defined between 2000 and 2022, although there were any articles before 2000 using the search string in Scopus. Furthermore, "Mexico" was used to reduce the search result to a Country. All articles were in the final stage of publication.

TABLE 2 Exclusion criteria for studies to be rejected.

Exclusion criteria	
Document type	Technical reports, conference papers, reviews, news, and thesis
Timeframe	Before 2000
Language	Other than English and Spanish
Country	Other than Mexico
Data type	Qualitative
Study focus	Other than energy recovery from wastewater

TABLE 3 Applied search strings and keywords.

Databases	Search string or keywords
Scopus	TITLE-ABS-KEY [("energy recovery" OR "energy harvesting" OR "power recovery" OR "energy production") AND wastewater]
Web of Science	ALL ("energy recovery" OR "energy harvesting" OR "power recovery" OR "energy production" AND wastewater)
Google Scholar	"recuperación de energía" OR "cosecha de energía" OR "producción de energía" OR "economía circular" + "agua residual" OR "tratamiento de agua residual" + Mexico OR México[a]

[a]Translation: "energy recovery" OR "energy harvesting" OR "energy production" OR "circular economy" + "wastewater" OR "wastewater treatment" + Mexico + México.

All data retrieved from the databases and the search engine was first exported to an excel document.

2.3 Study selection

The last date the database was scanned was November 15th of 2022. Figure 1 describes the selection process that was carried out for this work. A total of 313 articles were identified from Scopus, Web of Science, and Google Scholar to be screened and selected for inclusion.

Before the screening process, 61 works were removed: 29 representing duplicates and 32 representing other than peer-reviewed articles (thesis, news, congress articles). The title and abstract were read from the 313 articles to be screened and 281 works were excluded for not fulfilling the eligibility criteria. The remaining articles were assessed by full-text reading and 21 were excluded: 14 were out-of-scope articles, 6 were reviews, and 1 was not found. Additionally, 19 publications were included in bibliography searches. At the end of the selection process, just two articles in Spanish were included (Pérez-Grijalva et al., 2018) (Gómez-Paredes et al., 2020).

2.4 Data extraction and quality

The data of interest from the 31 studies selected for this review were extracted in a Microsoft Excel document to be further analyzed. Supplementary Table S1 exhibits the data collection. The latter included data from authors, publication year, magazine, keywords, name of the study, type of technology, type of energy recovery, type of wastewater, energy recovered, and specific data about the technology and specific case of the study carried around. If possible, missing parameters were calculated from data from the publication.

All strategies to gather data were discussed between the authors to ensure the validity of data and quality of itself. Furthermore, after the eligibility criteria and search strings were settled, the authors independently gathered the data and tougher resolved all the concerning disagreements that arouse. The authors had no competing interests.

3 Results

The gathered data from the 31 studies were used to assess the state of the question regarding the development of an energy recovery process using wastewater as a substrate. For every study, we added an index number to refer to it (N1 to N31). The oldest study assessed was from 2007, even though we limit the search to 2000. Table 4 summarizes the studies selected.

We realized a pattern of technologies being researched. There were three main categories in which the studies were divided based on the type of energy or energy product the researchers tried to develop: 1) methane (also known as biomethane); 2) hydrogen (also known as biohydrogen); and 3) electricity. It is worth remarking that study N24 was the only one that used bio-crude.

3.1 Publication trend

The results of our research of the 31 papers that we utilized in this review regarding the kind of product or direct energy recovered in those studies are presented in Figure 2. As the figure displays, there was a peak of research around the topic of this review in the year 2020, where biogas, including methane and hydrogen, was the most investigated subject. This (2020) was the year with the greatest number of studies produced. In the next 2 years (2021 and 2022, up to November), there was a decline of 50% in the first year and 90%

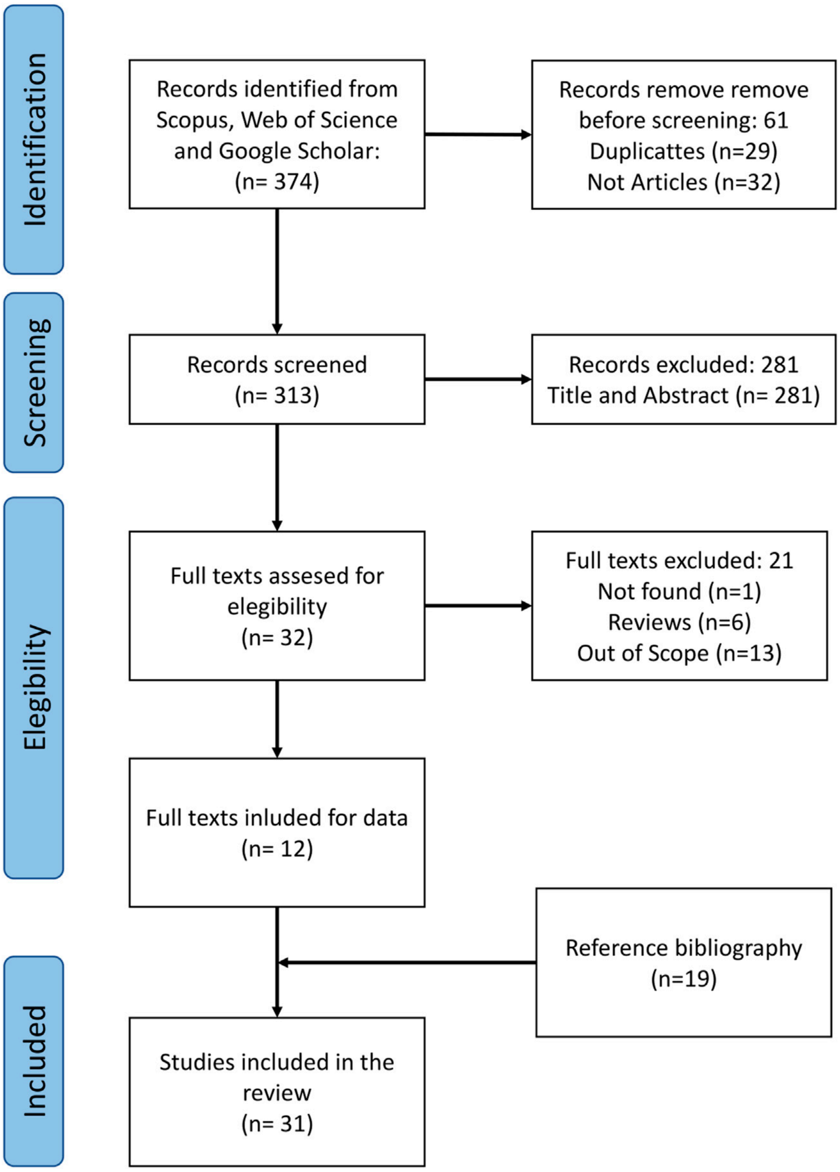

FIGURE 1
Identification of studies: PRISMA flow diagram.

in the second year. No studies were detected under our selection criteria from 2008–2011. The kind of energy recovery the most studied was electricity which ranged from 2012–2022, the year 2019 being the most active in the topic. Also, more than half of the studies were published in the past 4 years, since 2019.

Another thing to take into consideration is the COVID-19 pandemic: the worldwide non-COVID-19 research was reduced by 18% by 2021 (Raynaud et al., 2021). This could be due to editors dedicating less time to reviewing non-COVID-19 research or editors rejecting more papers than usual. Also, the impact of the restrictions during the pandemic needs to be taken into consideration. Most of the research obtained in this work was produced in closed environments such as laboratories.

The following are the publication trends concerning scientific journals and authors. The journals in which the selected papers were most published were Bioresource Technology, with three publications, and *Revista Mexicana de Ingeniería Química* (Mexican Journal of Chemical Engineering), with another three publications. They are followed by journals with two publications: Biomass and Bioenergy, International Journal of Hydrogen Energy, Water (Switzerland), and Water Science and Technology. The authors with more publications in the selected studies are Alzate-Gavira, Liliana, with seven publications, and Domínguez-Maldonado, Victor F., with four. Both of them are part of the Renewable Energy Unit of the Yucatán Center for Scientific Research A.C.

3.2 Technologies researched

Even though we identified four main energetic recovery products, the technology used to produce them and treat the wastewater at the same time was very diverse. They were 16 different types of

TABLE 4 Studies assessed for this work.

N	Author and year	Title	Substrate (wastewater)	Type of technology used	Type of energy or energy product
1	Alcaraz-Ibarra et al. (2020)	Treatment of chocolate-processing industry wastewater in a low-temperature pilot-scale UASB: reactor performance and *in situ* biogas use for bioenergy recovery	Chocolate-processing industry	UASB	Methane
2	Alzate-Gaviria et al. (2007)	Comparison of two anaerobic systems for hydrogen production from the organic fraction of municipal solid waste and synthetic wastewater	Synthetic	PBR and UASB	Hydrogen
3	Arreola-Vargas et al. (2016)	Biogas production in an anaerobic sequencing batch reactor by using tequila vinasses: effect of pH and temperature	Tequila vinasses	AnSBR	Methane
4	Burboa-Charis and Alvarez (2020)	Methane production from antibiotic-bearing swine wastewater using carbon-based materials as electrons' conduits during anaerobic digestion	Pig fattening farm	ABT with GAC and antibiotics	Methane
5	Carrillo-Reyes et al. (2019)	Influence of added nutrients and substrate concentration in biohydrogen production from winery wastewaters coupled with methane production	Red wine wastewater and effluent from anaerobic red wine wastewater treatment	ABT	Hydrogen and methane
6	Carrillo-Reyes et al. (2021)	Thermophilic biogas production from microalgae–bacteria aggregates: biogas yield, community variation, and energy balance	Primary effluent domestic water treatment plant and MABA sludge	HRAP and AnCSTR	Methane
7	Chacón-Carrera et al. (2019)	Assessment of two ionic exchange membranes in a bioelectrochemical system for wastewater treatment and hydrogen production	Enriched urban wastewater	MEC	Electricity and hydrogen
8	Diaz-Cruces et al. (2020)	Effect of lactate fermentation type on the biochemical methane potential of tequila vinasse	Tequila vinasses	LF and ABT	Methane
9	España-Gamboa et al. (2012)	Methane production by treating vinasses from hydrous ethanol using a modified UASB reactor	Hydrous ethanol vinasses	UASB	Methane
10	España-Gamboa et al. (2018)	Corn industrial wastewater (nejayote): a promising substrate in Mexico for methane production in a coupled system (APCR-UASB)	Nixtamalization wastewater (nejayote) and leachate from APCR	APCR and UASB	Methane
11	Alcaraz-Ibarra et al. (2020)	Treatment of chocolate industry wastewater in a pilot-scale low-temperature UASB reactor operated at short hydraulic and sludge retention time	Chocolate-processing industry wastewater	UASB	Methane
12	Estrada-Arriaga et al. (2017)	Performance of pig slurry-based microbial fuel cell during energy recovery and waste treatment	Pig slurry	Single chamber batch MFC	Electricity
13	Estrada-Arriaga et al. (2021)	Assessment of a novel single-stage integrated dark fermentation-microbial fuel cell system coupled with proton-exchange membrane fuel cell to generate bio-hydrogen and recover electricity from wastewater	Synthetic	DF-MFC and PEMFC	Electricity and hydrogen
14	García-Depraect et al. (2020a)	Upgrading of anaerobic digestion of tequila vinasse by using an innovative two-stage system with dominant lactate-type fermentation in acidogenesis	Tequila vinasses	CSTR and UASB	Hydrogen and methane

(Continued on following page)

TABLE 4 (*Continued*) Studies assessed for this work.

N	Author and year	Title	Substrate (wastewater)	Type of technology used	Type of energy or energy product
15	García-Depraect et al. (2020b)	Three-stage process for tequila vinasse valorization through sequential lactate, biohydrogen, and methane production	Tequila vinasses	Bioclave reactor, CSTR and UASB	Hydrogen and methane
16	Garita-Meza et al. (2022)	Maize processing wastewater for electricity production in a microbial electrochemical cell	Nixtamalization wastewater (nejayote)	Electrochemical cell	Electricity
17	Gómez-Paredes et al. (2020)	Industrial wastewater treatment by anaerobic digestion using a solar heater as renewable energy for temperature control	Mix of industrial wastewater (more than 50)	UASB with solar heater	Methane
18	González-Moreno et al. (2021)	Bioelectricity generation and production of ornamental plants in vertical partially saturated constructed wetlands	Domestic	CWMFC with *Z. aethiopica* and CWMFC with *Canna hybrids*	Electricity
19	Guadarrama-Perez et al. (2014)	Simultaneous bio-electricity and bio-hydrogen production in a continuous flow single microbial electrochemical reactor	Synthetic	sMER-h2	Electricity and hydrogen
20	Houbron et al. (2016)	Tratamiento de vinazas en un reactor de lecho fluidizado inverso anaerobio	Hydrous ethanol vinasses	IFBR	Methane
21	Linares et al. (2019)	Scale up of microbial fuel cell stack system for residential wastewater treatment in continuous mode operation	Domestic wastewater	Septic tank and MFC stack system (18 MECs)	Electricity
23	Moreno-Cervera et al. (2019)	Performance of a greywater cathode in a microbial fuel cell with three ion exchange membranes	Synthetic greywater	MFC (Utrex AMI-7001), MFC (Ultrex-CMI-7000) and MFC (Nafion 117)	Electricity
24	Nava-Bravo et al. (2021)	Catalytic hydrothermal liquefaction of microalgae cultivated in wastewater: influence of ozone-air flotation on products, energy balance, and carbon footprint	Secondary biological effluent	HRAP and microalgae harvesting (ozone-air flotation + catalytic HTL process)	Bio-crude
25	Pérez-Grijalva et al. (2018)	Design and evaluation of a sequential bioelectrochemical system for municipal wastewater treatment and voltage generation	Domestic	MFC (microbial fuel cell)	Electricity
26	Rochín-Wong, C.S. Gámez-Meza et al. (2012)	Acidogenesis/methanogenesis from acid cheese whey in hybrid UASB reactors	Acid whey wastewater	Acidogenic hybrid UASB and methanogenic hybrid UASB	Methane
27	Ruiz-Marin et al. (2020)	Biohydrogen production by *Chlorella vulgaris* and *Scenedesmus obliquus* immobilized cultivated in artificial wastewater under different light quality	Synthetic	PBR (with immobilized *S. obliquus*) in blue light	Hydrogen
28	Valero et al. (2018)	Enhancing biochemical methane potential and enrichment of specific electroactive communities from nixtamalization wastewater using granular activated carbon as a conductive material	Maize processing wastewater (nejayote)	ABT with GAC and antibiotics	Methane
29	Valero et al. (2020)	Rapid two-stage anaerobic digestion of nejayote through microaeration and direct interspecies electron transfer		APBR with microaeration and UASB	Methane
30	Vargas-Estrada et al. (2021)	Energy and nutrient recovery from wastewater cultivated microalgae: assessment of the impact of wastewater dilution on biogas yield	Domestic	Photobioreactors and biochemical methane potential test	Methane

(Continued on following page)

TABLE 4 (*Continued*) Studies assessed for this work.

N	Author and year	Title	Substrate (wastewater)	Type of technology used	Type of energy or energy product
31	Yazdi et al. (2015)	Pluggable microbial fuel cell stacks for septic wastewater treatment and electricity production	Synthetic	Three anaerobic MFC in parallel	Electricity

UASB, up-flow anaerobic sludge blanket; PBR, pack bed reactor; AnSBR, anaerobic sequencing batch reactor; ABT, anaerobic batch test; GAC, granulated activated carbon; HRAP, high-rate algal pond; AnCSTR, anaerobic stirred tank reactor; MEC, microbial electrolysis cell; LF, lactate fermentator; APCR, anaerobic-packed column reactor; DF-MFC, singles stage dark fermentation microbial cell; PEMFC, proton exchange membrane fuel cell; CSTR, continuously stirred tank reactor; CWMFC, constructed wetland microbial fuel cell; sMER-h2, single chamber hydrogen-producing microbial electrochemical reactor; IFBR, anaerobic inverse fluidized bed reactor; PBR, photobioreactor; APBR, anaerobic packed bed reactor.

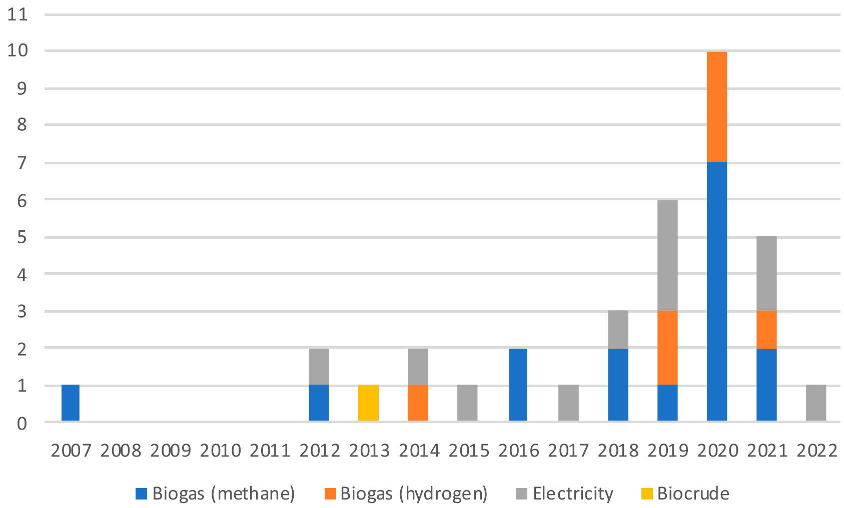

FIGURE 2
Trends in energy recovery from wastewater in Mexico from 2007 to 2022.

technologies applied in the studies reviewed. Figure 3 exhibits the proportion of the applied technologies. Microbial fuel cells (MFCs) were the most researched technologies, appearing in 27% of the studies, closely followed by up-flow sludge blanket (UASB) reactors, being on 24% of the studies. Anaerobic packed bed reactors (APBRs) were the third most used technology in the reviewed studies and represented 9%. Photobioreactors (PBRs), constructed wetlands (CWs), anaerobic batch tests (ABTs), anaerobic batch test with granular activated carbon (ABTGAC), high-rate algal ponds (HRAPs), anaerobic stirred tank reactors (AnSTRs), and microbial electrolysis cells (MECs) each represented 4% of the type of technology used in our research. “Others” refer to technologies that showed only one time in our process. They were as follows: anaerobic sequencing batch reactor (AnSBR), Bioclave bioreactor, dark fermentation reactor, algae harvesting reactor, electrochemical cell, and septic tank.

3.2.1 Technology trends

There were 15 selected studies that were conducted between 2020 and November 2022. That means almost half of the selected studies were conducted in the recent 3 years. One of the evident trends is microbial electrolysis and fuel cells, which accounted for almost half of the technologies represented in the studies. The development of hybrid embedded technologies, such as constructed wetlands + MFC, dark fermentation microbial cells, and using an MFC to treat high organic strength industrial wastewater, represent highlights in the recent reseach (N12, N16, and N18). It is important to note that UASB reactors continue to be a trend. They represent almost a third of these 2020–2022 selected studies. Furthermore, the use of anaerobic technologies represents almost two-thirds of these studies. This agrees with the fact that for these recent studies, the use of high-strength industrial wastewater, those from common Mexican industries, such as maize processing (nejayote), chocolate processing, and tequila vinasses, is widely utilized as the raw material because of their massive organic loading.

3.3 Type of energy product

There were four principal types of energy products identified in the research papers we reviewed: methane, hydrogen, electricity, and bio-crude. From the 31 studies, 38 cases were extracted because almost half of the studies (N2, N5, N6, N10, N13, N14, N15, N18, N21, N23, N24, N26, N29, and N30) tested more than one technology or different variations of the same. By far, the most energy product produced through wastewater in our selected works was methane, with 17 cases. A total of 11 studies encompassed subjects of electricity recovery, eight were about

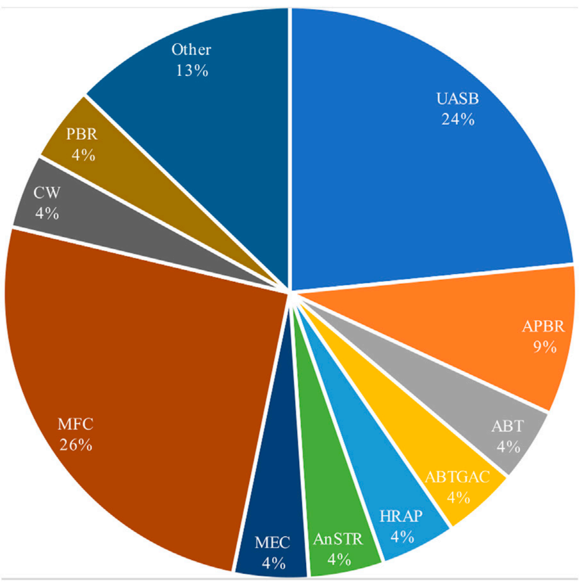

FIGURE 3
Different technologies for wastewater treatment and energy recovery researched in Mexico.

hydrogen recovery, and one was about bio-crude. There were only five studies where different kinds of energy products were tested in unison: N5, both methane and hydrogen; N13, biohydrogen and electricity; N14, both methane and hydrogen; N15, biogas, methane, and hydrogen; and N16, in which biohydrogen and electricity were tested in the same reactor.

3.4 Type of wastewater used as a substrate

Three main types of wastewater were spotted in our review. As regarded in Figure 4, the great majority (17) of studies targeted industrial wastewater. The subcategories of industrial wastewater, based on the cases previously presented, are displayed in Supplementary Table S1: vinasses with seven cases: N3, N5, N8, N9, N14, N15, and N20; industrial reactor effluent (I.R. effluent) with seven cases: N5, N10, N14, two in N15, N26, and N29; maize processing with four cases: N10, N16, N28, and N29; chocolate processing with two cases: N1 and N11; pig farming with two cases: N4 and N12; a mix of industrial with one case: N17; and acid whey with one case: N26. We refer to "reactor effluent" as the cases in which wastewater exits a previous reactor in the treatment train used in the study. Eight studies fell into the category of domestic wastewater: N6, N7, N18, N21, N24, N25, and N30. The subcategories were two: domestic with seven cases: N7, two in N18, N21, N24, N25, and N30 and domestic reactor effluent (D.R. effluent) with five cases: two in N6, N21, N24, and N30. Finally, six studies were identified into the category of synthetic wastewater. The subcategories were synthetic with nine cases: two in N2, N13, N19, three in N23, N27, and N31 and synthetic reactor effluent with one: N13.

3.5 Energy recovery

To connect and compare energy and pollutant removal technologies, taking into account their diversity and different configuration, the authors decided to evaluate them separately by the type of energetic product they recovered in the subsequent sections. However, the use of a baseline measurement was necessary to connect the biological byproducts of wastewater treatment with the energetic products and their potential to generate energy. Therefore, kWh/kg CODremoved was used as a unit to measure the capacity of systems to recover energy at the same time as removing pollutants from water. Only 13 studies were included in this part of our study because the lack of data from the articles prevented our team from calculating this parameter. Figure 5 represents the calculated kWh/kgCODremoved in these 13 studies. The estimations that Suhartini et al. (2019) proposed to calculate the energy yields for methane were used, and the estimations from IDIALHY for hydrogen (Idealhy.eu, 2022) were used. Figure 5 represents the calculated energy recovered in the studies. Four

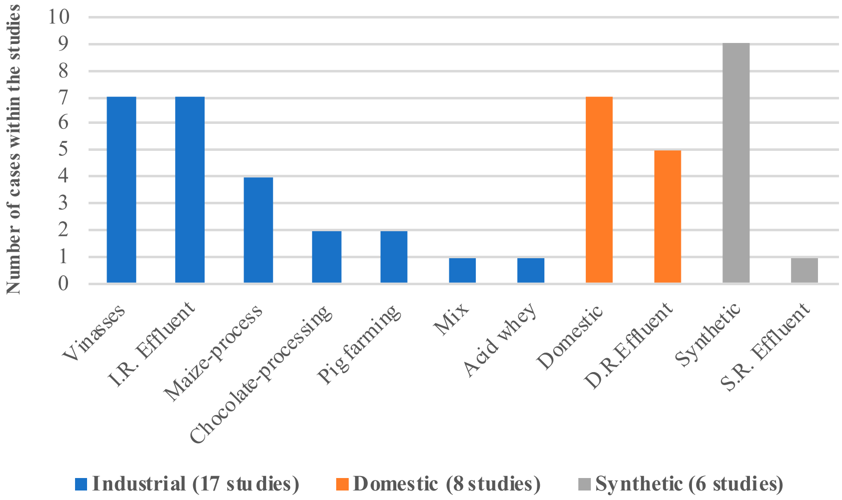

FIGURE 4
Type of wastewater treated to recover energy and number of cases in the selected studies.

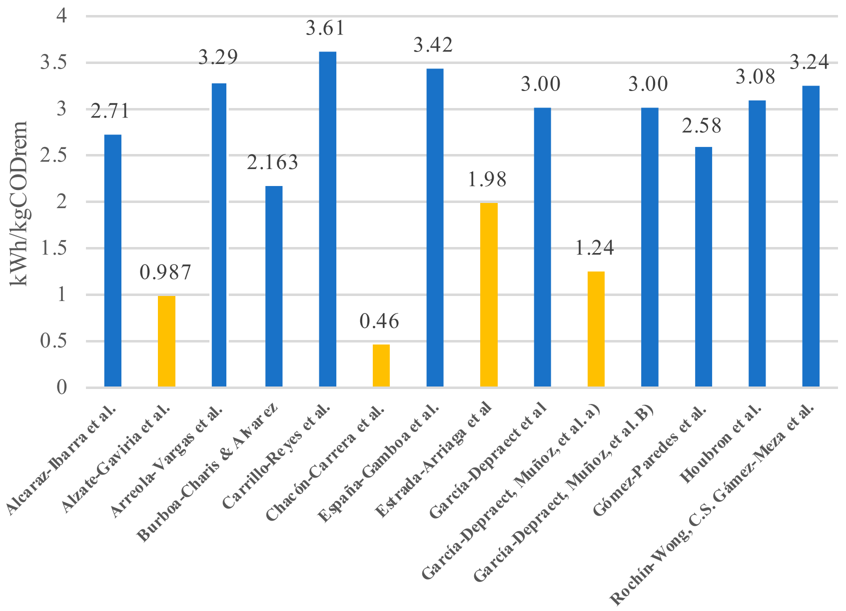

FIGURE 5
Energy obtained from the CODremoved from wastewater in this review.

TABLE 5 Methane production wastewater and basic parameters.

N	Type of technology used	Substrate (wastewater)	Subtype of wastewater	HTR (h)	OLR	V (L)	Production/yield
1	UASB	Chocolate-processing industry	Chocolate process	6.2	10.3 kgCOD/	244	432.3 L biogas/d
3	AnSBR	Tequila vinasses	Vinasses	4.8	1.04 kgCOD/m^3d	5.1	0.28 L CH_4/g COD added
4	ABT with GAC and antibiotics	Pig fattening farm	Pig farming	504	0.99 kgCOD/m^3d	0.06	0.0011 L biogas/d
5	ABT with nutrients added	Effluent from anaerobic red wine reactor treatment	Industrial reactor effluent	—	—	0.08	0.2 L CH4/g COD added
6	AnCSTR	MABA sludge	Domestic reactor effluent	—	1.1 kgVS/m^3d	1.5	0.41 m3 CH4/kgSV
8	LF and ABT	Tequila vinasses	Vinasses	48	29.200 kgCOD/ m^3d	2	0.437 m3 CH4/kgSV
9	UASB	Hydrous ethanol vinasses	Vinasses	180	17.05 kgCOD/m^3d	—	0.263 m3 CH4/kgSV
10	UASB	Leachate from APCR	Industrial reactor effluent	—	1.9 kgCOD/m^3d	2.78	0.308 L CH4/g COD added
11	UASB	Chocolate-processing industry wastewater	Chocolate processing	6.46	7 kgCOD/m^3d	244	431 L/d
14	UASB	Effluent from the CSTR	Industrial reactor effluent	96	10.1 kgCOD/m^3d	2	0.316 (L CH4/g COD added)
17	UASB with solar heater	Mix of industrial (more than 50)	Industrial	6	11.67 kgCOD/m^3d	2	—
20	IFBR	Hydrous ethanol vinasses	Vinasses	50	1 kgCOD/m^3d	1.7	—
26	Hybrid UASB	Effluent from AHUASB	Industrial reactor effluent	24	4.2 kgCOD/m^3d	4.3	4.96 L biogas/d
28	ABT with GAC and antibiotics	Maize processing (nejayote)	Maize process	—	—	0.12	0.297 m3 CH_4/kgSV
29	Hybrid UASB	Effluent from APBR	Industrial reactor effluent		4.6 kgCOD/m^3d		1.08 (L CH_4/L d)
30	Methane potential test	Effluent from photobioreactor	Domestic reactor effluent			0.12	6.59 mL CH_4/d

TABLE 6 Hydrogen production wastewater and basic parameters.

N	Type of technology used	Substrate (wastewater)	Subtype of wastewater	V (L)	HTR (h)	OLR	H2 production
14	CSTR	Tequila vinasses	Vinasses	3	24	52.1 (kgCOD/m^3/d)	0.43 (L H_2/L/d)
15	CSTR	Effluent from the lactate fermentator	Industrial reactor effluent	2	6	107 (gVS/kg d)	11.7 (L H2/L/d)
2	PBR	Synthetic	Synthetic	19.4	—	16 (gVS/kg d)	99 (mL H/gVS)
2	UASB	Synthetic	Synthetic	3.85	24	7 kg COD/m$_3$d	1.98 (mol H_2/mol glucose)
5	ABT without nutrients added	Red wine vinasses	Vinasses	0.07	—	—	528 (mL H2/L)
27	PBR glass flask (with immobilized S. obliquus) in blue light	Synthetic	Synthetic	1.5	—	—	0.204 (L H_2/L/d)
7	MEC	Enriched urban wastewater	Domestic	1	48	0.12 kgCOD/m$_3$d	10.3 (mg H_2/g COD)
13	DF-MFC	Synthetic	Synthetic	10	192	—	—
19	sMER-h2	Synthetic	Synthetic	10	8	—	2.4 (L H_2/L/d)

studies used hydrogen as the source of energy, all shown in yellow: N2 (Alzate-Gaviria et al., 2007), N7 (Chacón-Carrera et al., 2019), N13 (Estrada-Arriaga et al., 2021), and N15 (García-Depraect et al., 2020b; México reafirma compromisos de la Agenda 2030, 2022), the values of which are below the average that was 2.48 kWh/kg COD$_{removed}$ in this review. The best performance was attributed to N6 (Carrillo-Reyes et al., 2021), using an anaerobic stirred tank and effluent from a domestic reactor. According to our data, more energy per kgCOD removed could be obtained with methane-recovering technologies.

3.5.1 Methane production

Methane production was the most studied energy recovery process. Table 5 summarizes some of the technologies used in its production in addition to the type of wastewater and some important basic parameters. Because of the heterogeneity of the data and the lack of it in some cases, the results presented have their units as presented by the authors. The OLR varied from 0.99 to 29.2 kg COD/m^{3}d and reached production rates of 0.437 m^3 CH_4/kgVS for a batch test from a lactate fermentator (N8) or 0.316 L CH_4/g COD added for a UASB treating the effluent from a CSTR treating tequila vinasse (N14). The most frequently used technology to produce methane was UASB, with the studies from the section handling the subject. Most of the substrate to generate methane is highly strong wastewater coming from industry, except for one case (N6).

3.5.2 Hydrogen production

Hydrogen production, as represented in the studies reviewed, was carried out as a primary wastewater treatment process using high-strength industrial wastewater or synthetic wastewater resembling it. As presented in Table 6, the kind of technology used to recover hydrogen was wildly variable. Because of the heterogeneity of the data, or the lack of it in some cases, the results presented have their units as presented by the authors. OLR as high as 52.1 kg COD/m^3 L and 107 gVS/kg d were presented in two works (N14 and N15) that both used a continuously stirred tank. It is worth mentioning that MFCs, combined with dark fermentation, and MECs have been present in hydrogen recovery from wastewater since 2014 in Mexico. As shown in the aforementioned case with methane, wastewater from industries with high organic loads is primarily used to produce hydrogen. Hydrogen production varies from 0.204 L H_2/L/d produced by a photobioreactor treating synthetic domestic water (N19) to 11.7 L H_2/L/d by a continuously stirred reactor treating effluents in a lactate fermentation tank (N15).

3.5.3 Electricity production

The studies within our review that focused on recovering electricity from wastewater mostly used microbial fuel cells in seven out of nine studies. As presented in Table 7, the most used ion separation membrane was Nafion 117 and, when compared with Ultrex CMI-7000 and Ultrex CMI-7001, produced a volumetric power density of 205.5 mW/m^3, as presented in the N23 study. Double chamber types were the most numerous, followed by air cathodes, and the distance between electrodes was never more than 10.1 cm. The maximum voltage generated ranges from 83 to 820.35 mV. There was one hybrid pilot-scale study (N18) in which two vertically constructed wetlands and activated carbon sheets as anode and cathode were used. In addition to generating a power density of 6.4 and 9.7 mW/m^2 with two different species of plants (*Canna hybrids* and *Z. aethiopica*, respectively), it also had COD removal percentages of 98.9 and 98.1 in treating domestic wastewater.

3.6 Further research suggested in the studies

Most of the further research suggestions regarding energy recovery presented in the selected studies revolved around using new or modified variables over the same trials. In the case of methane production, Burboa and Alvarez suggested that future trials should include a large period in a continuous instead of a batch mode to "evaluate the if the capacity of carbon materials to act as electron conduits is maintained, because the adsorption of undesirable compounds may limit the mass transfer to and from the material" (Burboa-Charis and Alvarez, 2020). Moreover, Carrillo-Reyes et al. (2021) suggested that future trials in their thermophilic anaerobic digestion system must use protein removal from the microalga-bacteria aggregates biomass during anaerobic digestion with the

TABLE 7 Electricity production wastewater and basic parameters.

N	Type of technology used	Substrate (wastewater)	Max. generated (mV)	Current density (mA/m^2)	Vol. Power density (mW/m^3)	Power density (mW/m^2)	Anode	Cathode	MFC/MEC type	Separator/ion exchange membrane	Distance between electrodes (cm)
7	MEC	Enriched urban WW				9.9	Graphite	Platinum electrode	Double chamber	Nafion 117	
12	Single chamber batch MFC	Pig slurry	83	3.5		24.8	Carbon cloth	Carbon fiber w/ PbO2 impregnated + cation exchange membrane	Single chamber		10.1
13	PEMFC	Effluent from DF-MFC	459				Three anodes of carbon felt	Two cathodes of carbon cloth with lead powder	Air cathode		5
16	Electrochemical cell	Maize- process (nejayote)					Ag/AgCl	Carbon felt			
18	CWMFC with *Z. aethiopica*	Domestic	450	65		9.7	AC sheets	Activated carbon sheets			
	CWMFC with *Canna hybrids*	Domestic	750	140		6.4	AC sheets	Activated carbon sheets			
19	sMER-h2	Synthetic	240		820	5.88	Three carbon felts	Two carbon clothes	Air cathode	Carbon cloth	
21	MFC stack system (18 MECs)	Effluent from the septic tank	382				Granular carbon + stainless steel mesh	Carbon cloth with vulcan carbon	Air cathode	CEM Nafion 117	5
23	MFC (Utrex AMI-7001)	Synthetic greywater	1667.15		178.74		Granular carbon and stainless steel mesh	Granular carbon and stainless steel mesh	Two chamber	Nafion 117	
	MFC (Ultrex-CMI-7000)	Synthetic greywater	820.35		71.57		Granular carbon and stainless steel mesh	Granular carbon and stainless steel mesh	Two chamber	Ultrex CMI-7000	
	MFC (Nafion 117)	Synthetic greywater	1951.4		201.5		Granular carbon and stainless steel mesh	Granular carbon and stainless steel mesh	Two chamber	Ultrex AMI-7001	
25	MFC	Domestic	93.2		0.2202		Poliurethane/ graphite/ polipirrol	Poliurathane/graphite	Two chamber (aerobic/ anaerobic)		
31	Three anaerobic MFC in parallel	Synthetic	320			142	Activated carbon cloth	Three layers of polymethylsilo-xane on activated carbon cloth	Air cathode	J-cloth	

intention to reduce the inhibition produced by free ammonia from the protein degradation. Furthermore, they suggest that future investigation should be based on a higher organic loading rate (OLR> 2 kgVS m^{-3} d^{-1}) because no inhibition by the accumulation of volatile fatty acids was observed in the system. For the case of hydrogen production, García-Depraect et al. (2020a) advised that further studies on lactate-type fermentation in acidogenesis must focus on both "the structural diversity and functionality of microbial communities involved in the different fermentation stages" to produce hydrogen and in the next step methane in a more efficient way. For the case of electricity production, Chacón-Carrera et al. (2019) suggested that future attempts to exploit bipolar membranes of microbial electrochemical systems must take notice of using, for instance, another type of cathode material with greater surface area (they used platinum electrode 1 cm^2) using an acid buffer to benefit oxidation of acetate in the reactor and wastewater with higher COD levels and good conductivity

4 Discussion

One of the main findings in this review was that there are three principal ways in which Mexican research addresses the issues of both wastewater and energy recovery: methane, hydrogen, and bioelectricity. We found only one study that directly addressed bio-crude. This agrees with the study by Meneses-Jácome et al. (2016), who found that biohydrogen and MECs were the most researched in Mexico. Although before that year, less than a third of the studies gathered in this work had been published yet.

Possibly, Mexico has not bet on energy recovery wastewater treatment technologies because it has enormous potential through the alternative sources of energy mentioned before. Nevertheless, the fact that technology is being created in the country with the capacity to treat wastewater and at the same time recover energy from it is transcendental because it addresses two fundamental issues: the overabundant amount of untreated wastewater that is discharged into the environment and the consequences of the excessive use of oil to generate energy. In addition, research has shown successful exercises to power wastewater treatment plants using the energy recovered from wastewater (Gutierrez, 2018). These could encourage municipal water utilities to apply these technologies.

The decline of studies from last year (2021) in the publication of studies regarding the topic of our research could be caused by the number of studies focusing on co-digestion instead of using only wastewater as substrate. Co-digestion was the most discarded study in the screening process at the beginning of this work. Also, this could be attributed to the change of approach in the legislation and political action toward energy policy. As mentioned before, the Federal Administration has changed toward a heavily centralized fossil fuel energy production from which the CFE (Federal Electricity Commission) has greatly benefited. Also, it could be attributed to the COVID-19 worldwide pandemic, when non-COVID-19 research fell by around 18%.

One reason for this many studies using industrial wastewater could be that it represents the most organic concentrate wastewater, which can be used to produce more energy with less volume of the substrate. In the studies, domestic wastewater was used more commonly in studies where MECs and MFCs were researched. The kind of application was different from those producing methane or hydrogen. Energy recovery by producing electricity using MECs was specifically designed to be decentralized wastewater treatment plants, where the energy is produced during the wastewater treatment. It is worth noting that energy recovery in the form of electricity was depicted in most cases as a way to be neutral in terms of energy, not to be energy positive. Except for one study (N16), all of the studies producing electricity using MECs used domestic wastewater.

In Mexico, the research conceptually regarded as energy recovery from wastewater began in 2007, according to our gathered data. The first study identified as "energy recovery" from wastewater found in this work was a 2007 study (Alzate-Gaviria et al., 2007), and it addressed topics around hydrogen generation. Additionally, the first study identified in Mexico concerning MFC was published in 2014. Research on biogas production from wastewater has been carried out in Mexico since 1990 (Guyot et al., 1990). The turning point was identified when scientific research began to consider recovering energy as a concept, not only biogas production, as was the previously mentioned work by Alzate-Gaviria et al. (2007).

The microbial communities and the operational conditions are presented as research gaps most commonly. At each site where the same biological wastewater treatment and energy recovery technology is managed, the general conditions of the surrounding environment diverge from each other, which not only results in well-known changes in operational conditions but also results in a wide variety of local microorganisms and substrates. The composition and the relationship between its members is an issue that deserves further research: how the microbial community affects wastewater treatment and energy recovery technology performance? How the composition of the microbial community affects the technology yield? Which are the perfect operational conditions that allow for improvement in energy recovery yields for each heavily organic-loaded wastewater in the country?

As previously mentioned, recovering energy through methane generated from wastewater is a well-studied and implemented technology in Mexico (Ramírez-Higareda et al., 2019), whereby the majority of studies revolved around it. The fact that methane production technologies were mostly fed with wastewater coming from a high-pollutant industry is expected because it is known by the industry sector that it is not only a way to regenerate the quality of water but also to generate "free" renewable energy (Hamawand, 2015). Additionally, large-scale agribusinesses know that they can rely upon bio-methanation to recover a fair amount of energy through anaerobic wastewater treatment and co-digestion and initial construction investment. Juice producers, pig farms and slaughterhouses, chocolate processing plants, and tequila industries treat their wastewater with anaerobic processes to produce biogas. Also, Mexico already has a great human capital trained to operate anaerobic biogas-producing technologies.

5 Conclusion

Research on energy recovery technology using wastewater treatment processes in Mexico is still an ongoing field of research. As in all other research areas, the COVID-19 pandemic had a negative effect on the volume of research. Even so, the increase in research on this topic had a substantial growth since 2019, compared to all the years since 2007. The technologies' operating conditions and the reactors' microbial community composition are the most numerous gaps in Mexican research. Since anaerobic processes for wastewater treatment are the most used in Mexico for energy recovery in the industry, it is consistent that most of the articles included in this study revolved around it. We can also highlight the growing interest in the development of hybrid systems, using MFCs and MECs as their main treatment and energy recovery components.

Although Mexico has great potential for energy generation through renewable sources, leaving fossil fuels behind, energy recovery through wastewater treatment systems helps to mitigate in unison the major problem of untreated wastewater discharges to the environment and to leave aside fossil fuels with all the negative impacts they entail.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

MO-S contributed to the conception and design of the study and wrote the first draft of the manuscript. MO-S and GC-R organized the database. MO-S and GC-R contributed to the manuscript revision and approved the submitted version.

Conflict of interest

The remaining author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2023.1116053/full#supplementary-material

References

Agyekum, T. P., Antwi-Agyei, P., and Dougill, A. J. (2022). The contribution of weather forecast information to agriculture, water, and energy sectors in east and west Africa: A systematic review. *Front. Environ. Sci.* 10, 1–14. doi:10.3389/fenvs.2022.935696

Alcaraz-Ibarra, S., Mier-Quiroga, M. A., Esparza-Soto, M., Lucero-Chávez, M., and Fall, C. (2020). Treatment of chocolate-processing industry wastewater in a low-temperature pilot-scale UASB: Reactor performance and *in-situ* biogas use for bioenergy recovery. *Biomass Bioenergy* 142, 105786. doi:10.1016/j.biombioe.2020.105786

Alzate-Gaviria, L. M., Sebastian, P. J., Pérez-Hernández, A., and Eapen, D. (2007). Comparison of two anaerobic systems for hydrogen production from the organic fraction of municipal solid waste and synthetic wastewater. *Int. J. Hydrogen Energy* 32, 3141–3146. doi:10.1016/j.ijhydene.2006.02.034

Arreola-Vargas, J., Jaramillo-Gante, N. E., Celis, L. B., Corona-González, R. I., González-Álvarez, V., and Méndez-Acosta, H. O. (2016). Biogas production in an anaerobic sequencing batch reactor by using tequila vinasses: Effect of pH and temperature. *Water Sci. Technol.* 73 (3), 550–556. doi:10.2166/wst.2015.520

Burboa-Charis, V. A., and Alvarez, L. H. (2020). Methane production from antibiotic bearing swine wastewater using carbon-based materials as electrons' conduits during anaerobic digestion. *Int. J. Energy Res.* 44 (13), 10996–11005. doi:10.1002/er.5616

Carrillo-Reyes, J., Albarrán-Contreras, B. A., and Buitrón, G. (2019). Influence of added nutrients and substrate concentration in biohydrogen production from winery wastewaters coupled to methane production. *Appl. Biochem. Biotechnol.* 187 (1), 140–151. doi:10.1007/s12010-018-2812-5

Carrillo-Reyes, J., Buitrón, G., Arcila, J. S., and López-Gómez, M. O. (2021). Thermophilic biogas production from microalgae-bacteria aggregates: Biogas yield, community variation and energy balance. *Chemosphere* 275, 129898. doi:10.1016/j.chemosphere.2021.129898

Catalán, H. (2020). Impacto de las energías renovables en las emisiones de gases efecto invernadero en México. *Probl. Del Desarro. Rev. Latinoam. Econ.* 52, 69611. doi:10.22201/iiec.20078951e.2021.204.69611

Chacón-Carrera, R. A., López-Ortiz, A., Collins-Martínez, V., Meléndez-Zaragoza, M. J., Salinas-Gutiérrez, J., Espinoza-Hicks, J. C., et al. (2019). Assessment of two ionic exchange membranes in a bioelectrochemical system for wastewater treatment and hydrogen production. *Int. J. Hydrogen Energy* 44 (24), 12339–12345. doi:10.1016/j.ijhydene.2018.10.153

CONAGUA (2019). Estadísticas del Agua en México 2019. SEGOB. Available at: https://www.gob.mx/conagua.

CONAGUA-JICA (2012). *Cooperación técnica México japón*. Morelos, Mexico: CONAGUA (National Water Comission).

Diaz-Cruces, V. F., García-Depraect, O., and León-Becerril, E. (2020). Effect of lactate fermentation type on the biochemical methane potential of tequila vinasse. *Bioenergy Res.* 13 (2), 571–580. doi:10.1007/s12155-020-10093-z

Emenekwe, C. C., Okereke, C., Nnamani, U. A., Emodi, N. V., Diemuodeke, O. E., and Anieze, E. E. (2022). Macroeconomics of decarbonization strategies of selected Global South countries: A systematic review. *Front. Environ. Sci.* 10, 1–24. doi:10.3389/fenvs.2022.938017

España-Gamboa, E., Domínguez-Maldonado, J. A., Tapia-Tussell, R., Chale-Canul, J. S., and Alzate-Gaviria, L. (2018). Corn industrial wastewater (nejayote): A promising substrate in Mexico for methane production in a coupled system (APCR-UASB). *Environ. Sci. Pollut. Res.* 25 (1), 712–722. doi:10.1007/s11356-017-0479-z

España-Gamboa, E. I., Mijangos-Cortés, J. O., Hernández-Zárate, G., Maldonado, J. A. D., and Alzate-Gaviria, L. M. (2012). Methane production by treating vinasses from hydrous ethanol using a modified UASB reactor. *Biotechnol. Biofuels* 5, 82. doi:10.1186/1754-6834-5-82

Estrada-Arriaga, E. B., Bahena-Bahena, E. O., García-Sánchez, L., and González-Rodríguez, J. G. (2017). Performance of pig slurry based microbial fuel cell during energy recovery and waste treatment. *Desalination Water Treat.* 64, 31–39. doi:10.5004/dwt.2017.20165

Estrada-Arriaga, E. B., Hernández-Romano, J., Mijaylova-Nacheva, P., Gutiérrez-Macías, T., and Morales-Morales, C. (2021). Assessment of a novel single-stage integrated dark fermentation-microbial fuel cell system coupled to proton-exchange membrane fuel cell to generate bio-hydrogen and recover electricity from wastewater. *Biomass Bioenergy* 147, 106016. doi:10.1016/j.biombioe.2021.106016

García-Depraect, O., Diaz-Cruces, V. F., and León-Becerril, E. (2020a). Upgrading of anaerobic digestion of tequila vinasse by using an innovative two-stage system with dominant lactate-type fermentation in acidogenesis. *Fuel* 280, 118606. doi:10.1016/j.fuel.2020.118606

García-Depraect, O., Muñoz, R., van Lier, J. B., Rene, E. R., Diaz-Cruces, V. F., and León-Becerril, E. (2020b). Three-stage process for tequila vinasse valorization through sequential lactate, biohydrogen and methane production. *Bioresour. Technol.* 307, 123160. doi:10.1016/j.biortech.2020.123160

Garita-Meza, M. A., Contreras-Bustos, R., and Cercado, B. (2022). Maize processing wastewater for electricity production in a microbial electrochemical cell. *Biocatal. Agric. Biotechnol.* 44, 102481. doi:10.1016/j.bcab.2022.102481

Gómez-Paredes, M. D., Hernández-Rodríguez, I. A., López-Ortega, J., González-Blanco, G., and Beristain-Cardoso, R. (2020). Industrial wastewater treatment by anaerobic digestion using a solar heater as renewable energy for temperature-control. *Rev. Mex. Ing. Quimica* 19, 9–16. doi:10.24275/rmiq/IA1853

González-Moreno, H. R., Marín-Muníz, J. L., Sánchez-Dela-cruz, E., Nakase, C., Del Ángel-Coronel, O. A., Reyes-Gonzalez, D., et al. (2021). Bioelectricity generation and production of ornamental plants in vertical partially saturated constructed wetlands. *WaterSwitzerl.* 13 (2), 143. doi:10.3390/w13020143

Guadarrama-Perez, O., Hernandez-Romano, J., Garcıa-Sanchez, L., Gutierrez-Macias, T., and Estrada-Arriaga, E. B. (2014). Simultaneous bio-electricity and bio-hydrogen production in a continuous flow single microbial electrochemical reactor. *Environ. Prog. Sustain. Energy* 33 (3), 676–680. doi:10.1002/ep

Gutierrez, J. P. (2018). Situación actual y escenarios para el desarrollo del biogás en México hacia 2024 y 2030 Red Mexicana De Bioenergia A.C. Red Tematica De Bioenergia De Conacyt. Available at: https://rembio.org.mx/wp-content/uploads/2020/11/Situacion-actual-y-escenarios-para-el-desarrollo-del-biogas-en-Mexico.pdf.

Guyot, J. P., Macarie, H., and Noyola, A. (1990). Anaerobic digestion of a Petrochemical Wastewater using the UASB process. *Appl. Biochem. Biotechnol.* 24–25 (1), 579–589. doi:10.1007/BF02920280

Hamawand, I. (2015). Anaerobic digestion process and bio-energy in meat industry: A review and a potential. *Renew. Sustain. Energy Rev.* 44, 37–51. doi:10.1016/j.rser.2014.12.009

Houbron, E., Sandoval Rojas, M. E., and Hernández Muñoz, A. F. (2016). Tratamiento de vinazas en un reactor de lecho fluidizado inverso anaerobio. *Rev. Int. Contam. Ambient.* 32 (3), 255–266. doi:10.20937/RICA.2016.32.03.01

idealhy.eu (2022). idealhy.eu - liquid hydrogen outline. Available at: https://www.idealhy.eu/index.php?page=lh2_outline.

INEGI (2020). *Anuario estadístico INEGI 2020*. Instituto Nacional de Estadística Geografía e Informática.

Linares, R. V., Domínguez-Maldonado, J., Rodríguez-Leal, E., Patrón, G., Castillo-Hernández, A., Miranda, A., et al. (2019). Scale up of microbial fuel cell stack system for residential wastewater treatment in continuous mode operation. *WaterSwitzerl.* 11 (2), 217–316. doi:10.3390/w11020217

Lorick, D., Macura, B., Ahlström, M., Grimvall, A., and Harder, R. (2020). Effectiveness of struvite precipitation and ammonia stripping for recovery of phosphorus and nitrogen from anaerobic digestate: A systematic review. *Environ. Evid.* 9 (1), 27–20. doi:10.1186/s13750-020-00211-x

Martínez Hernández, F. A., and Aguilar, S. H. (2021). Pemex, su reestructuración corporativa, financiera y productiva, y los efectos de ésta sobre la balanza comercial petrolera. *Trimest. Econ.* 88 (349), 143–180. doi:10.20430/ETE.V88I349.1005

Masera, O., and Sacramento, J. C. (2022). Promoting a sustainable energy transition in Mexico: The role of solid biofuels. *BioEnergy Res.* 15, 16911691–16911693. doi:10.1007/s12155-022-10540-z

Meneses-Jácome, A., Diaz-Chavez, R., Velásquez-Arredondo, H. I., Cárdenas-Chávez, D. L., Parra, R., and Ruiz-Colorado, A. A. (2016). Sustainable Energy from agro-industrial wastewaters in Latin-America. *Renew. Sustain. Energy Rev.* 56, 1249–1262. doi:10.1016/j.rser.2015.12.036

México reafirma compromisos de la Agenda 2030 (2022). Secretaría de Relaciones Exteriores Gobierno gob.mx. Available at: https://www.gob.mx/sre/prensa/mexico-reafirma-compromisos-de-la-agenda-2030?idiom=es.

Moreno-Cervera, R., Aguilar-Vega, M., Domínguez-Maldonado, J., Cámara-Chale, G., and Alzate-Gaviria, L. (2019). Performance of a greywater cathode in a microbial fuel cell with three ion exchange membranes. *J. Chem. Technol. Biotechnol.* 94 (5), 1601–1612. doi:10.1002/jctb.5927

Muzioreva, H., Gumbo, T., Kavishe, N., Moyo, T., and Musonda, I. (2022). Decentralized wastewater system practices in developing countries: A systematic review. *Util. Policy* 79, 101442. doi:10.1016/j.jup.2022.101442

Nava-Bravo, I., Velasquez-Orta, S. B., Monje-Ramírez, I., Güereca, L. P., Harvey, A. P., Cuevas-García, R., et al. (2021). Catalytic hydrothermal liquefaction of microalgae cultivated in wastewater: Influence of ozone-air flotation on products, energy balance and carbon footprint. *Energy Convers. Manag.* 249, 114806. doi:10.1016/j.enconman.2021.114806

Page, M. J., Moher, D., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., et al. (2021). PRISMA 2020 explanation and elaboration: Updated guidance and exemplars for reporting systematic reviews. *BMJ* 372, n160. doi:10.1136/bmj.n160

Pérez-Grijalva, B., García-Zebadúa, J. C., Ruíz-Pérez, V. M., Téllez-Medina, D. I., García-Pinilla, S., Guzmán-Gerónimo, R. I., et al. (2018). Design and evaluation of a sequential bioelectrochemical system for municipal wastewater treatment and voltage generation. *Rev. Mex. Ing. Quimica* 17 (1), 13–28.

Ramírez-Higareda, B. L., Leyva-Huitrón, R., Chimil-Molina, R., López-Hernández, J. E., and Harder, B. (2019). *Biogas plants in Denmark and Mexico*. Online: Danish Energy Agency.

Raynaud, M., Goutaudier, V., Louis, K., Al-Awadhi, S., Dubourg, Q., Truchot, A., et al. (2021). Impact of the COVID-19 pandemic on publication dynamics and non-COVID-19 research production. *BMC Med. Res. Methodol.* 21 (1), 255–310. doi:10.1186/s12874-021-01404-9

Rico, G., Luis, E., Mozur, G., Gil, R., Rosa, E., and Armas, D. (2007). Los macroprocesos de la Industria petrolera y sus consecuencias ambientales. *Univ. Cienc. Tecnol.* 11, 91–97.

Rochín-Wong, C. S., Gámez-Meza, N., Montoya-Ballesteros, L. C., and Medina-Juárez, L. A. (2012). Acidogenesis/methanogenesis from acid cheese whey in hybrid-UASB reactors. *Rev. Mex. Ing. Quím.* 11 (1), 23–43.

Ruiz-Marin, A., Canedo-López, Y., and Chávez-Fuentes, P. (2020). Biohydrogen production by Chlorella vulgaris and Scenedesmus obliquus immobilized cultivated in artificial wastewater under different light quality. *Amb. Express* 10 (1), 191. doi:10.1186/s13568-020-01129-w

Solarin, S. A. (2020). An environmental impact assessment of fossil fuel subsidies in emerging and developing economies. *Environ. Impact Assess. Rev.* 85, 106443. doi:10.1016/j.eiar.2020.106443

Suhartini, S., Lestari, Y. P., and Nurika, I. (2019). Estimation of methane and electricity potential from canteen food waste. *IOP Conf. Ser. Earth Environ. Sci.* 230 (1), 012075. doi:10.1088/1755-1315/230/1/012075

The World Bank (2023). Upper middle income | Data. Available at: https://data.worldbank.org/country/XT.

Valero, D., Rico, C., Canto-Canché, B., Domínguez-Maldonado, J. A., Tapia-Tussell, R., Cortes-Velazquez, A., et al. (2018). Enhancing biochemical methane potential and enrichment of specific electroactive communities from nixtamalization wastewater using granular activated carbon as a conductive material. *Energies* 11 (8), 2101. doi:10.3390/en11082101

Valero, D., Rico, C., Tapia-Tussell, R., and Alzate-Gaviria, L. (2020). Rapid two stage anaerobic digestion of nejayote through microaeration and direct interspecies electron transfer. *Processes* 8 (12), 1614–1615. doi:10.3390/pr8121614

Vargas-Estrada, L., Longoria, A., Okoye, P. U., and Sebastian, P. J. (2021). Energy and nutrients recovery from wastewater cultivated microalgae: Assessment of the impact of wastewater dilution on biogas yield. *Bioresour. Technol.* 341, 125755. doi:10.1016/j.biortech.2021.125755

Yazdi, H., Alzate-Gaviria, L., and Ren, Z. J. (2015). Pluggable microbial fuel cell stacks for septic wastewater treatment and electricity production. *Bioresour. Technol.* 180, 258–263. doi:10.1016/j.biortech.2014.12.100

Zarei, M. (2020). Wastewater resources management for energy recovery from circular economy perspective. *Water-Energy Nexus* 3, 170–185. doi:10.1016/j.wen.2020.11.001