energies

Review

The Current Status and Future Potential of Biogas Production from Canada's Organic Fraction Municipal Solid Waste

Omid Norouzi and Animesh Dutta *

School of Engineering, University of Guelph, Guelph, ON N1G2W1, Canada; Norouzio@uoguelph.ca
* Correspondence: adutta@uoguelph.ca; Tel.: +1-519-824-4120 (ext. 52441)

Abstract: With the implementation of new policies supporting renewable natural gas production from organic wastes, Canada began replacing traditional disposal methods with highly integrated biogas production strategies. Herein, data from published papers, Canadian Biogas Association, Canada's national statistical agency, and energy companies' websites were gathered to gain insight into the current status of anaerobic digestion plants in recovering energy and resource from organic wastes. The availability of materials prepared for recycling by companies and local waste management organizations and existing infrastructures for municipal solid waste management were examined. Governmental incentives and discouragements in Canada and world anaerobic digestion leaders regarding organic fraction municipal solid waste management were comprehensively reviewed to identify the opportunities for developing large-scale anaerobic digestion in Canada. A range of anaerobic digestion facilities, including water resource recovery facilities, standalone digesters, and on-farm digesters throughout Ontario, were compared in terms of digestion type, digester volume, feedstock (s), and electricity capacity to better understand the current role of biogas plants in this province. Finally, technology perspectives, solutions, and roadmaps were discussed to shape the future in terms of organic fraction municipal solid waste management. The findings suggested that the biogas industry growth in Canada relies on provincial energy and waste management policies, advanced technologies for diverting organic waste from landfills, improving biogas yield using existing pretreatment methods, and educating farmers regarding digester operations.

Keywords: waste management; organic waste; anaerobic digestion; biogas plant; pretreatment; Canada

check for updates

Citation: Norouzi, O.; Dutta, A. The Current Status and Future Potential of Biogas Production from Canada's Organic Fraction Municipal Solid Waste. *Energies* **2022**, *15*, 475. https://doi.org/10.3390/en15020475

Academic Editor: Dino Musmarra

Received: 12 December 2021
Accepted: 7 January 2022
Published: 10 January 2022

1. Introduction

The Canadian economy currently seems locked into an inefficient system. Production, economics, contracts, regulation, and consumer behaviour all favor the linear model of production and consumption. This model applies to our current food industry and is very wasteful. Between 33% and 50% of food is wasted, and many food production techniques cause widespread environmental degradation [1,2]. The situation will exacerbate within the next 30 years due to population growth and shifting demographics. The current waste management strategies, which mostly rely on thermal conversion by incineration, do not encourage recycling and waste reduction. This is not a strong long-term strategy for society. Nowadays, there is a significant worldwide trend of promulgating regulations and policies banning organic fraction municipal waste (OFMSW) from entering landfills [3]. Due to encouraging or enforcing Canadian policies on biogas plants, anaerobic digestion (AD) has been considered a suitable method for converting organic waste streams into renewable energy and fertilizer. Feed-in tariff (FIT) policies that encourage renewable natural gas (RNG) from AD resulted in the implementation of many biogas plants in Canada [3]. However, to reach the global PARIS Agreement and join the biogas leaders (Germany, the UK, Japan, Italy, Spain, Denmark, Sweden, and China), Canada should focus more on reforming its renewable energy policies and economic incentives [4–6].

Canada generates 35.5 million tonnes of waste containing 20% to 40% OFMSW [7]. This amount of OFMSW can be converted into about 12,000 kWh of renewable energy per year [8]. In Canada, the current waste management infrastructures can only capture 2.6 million tonnes of OFMSW from landfills (Figure 1) [9]. Figure 2 shows the proportion of organic waste diverted from municipal waste in Canada by province. Among the provinces, New Brunswick diverted the most organics (57.57%), followed by Nova Scotia (46.84%), Prince Edward Island (36%), British Columbia (35.33%), Alberta (34.62%), Ontario (34.27%), Manitoba (25.38%), Newfoundland (21.57%), Saskatchewan (16.98%), and Yukon (15.69%) [10]. In these provinces, managing technologies to establish OFMSW includes biological and thermochemical conversion systems such as composting, AD, hydrothermal carbonization (HTC), pyrolysis, gasification, and incineration. Among all others, anaerobic digestion seems to be a more sustainable system and can be integrated with or replace conventional waste management strategies more efficiently. AD is becoming an important technology in the conversion of OFMSW, waste-activated sludge (WAS), agricultural waste, animal manure, and food waste. Further information on life cycle assessment (LCA) and life cycle cost (LCC) of AD of OFMSW can be found in a study by Demichelis et al. [11].

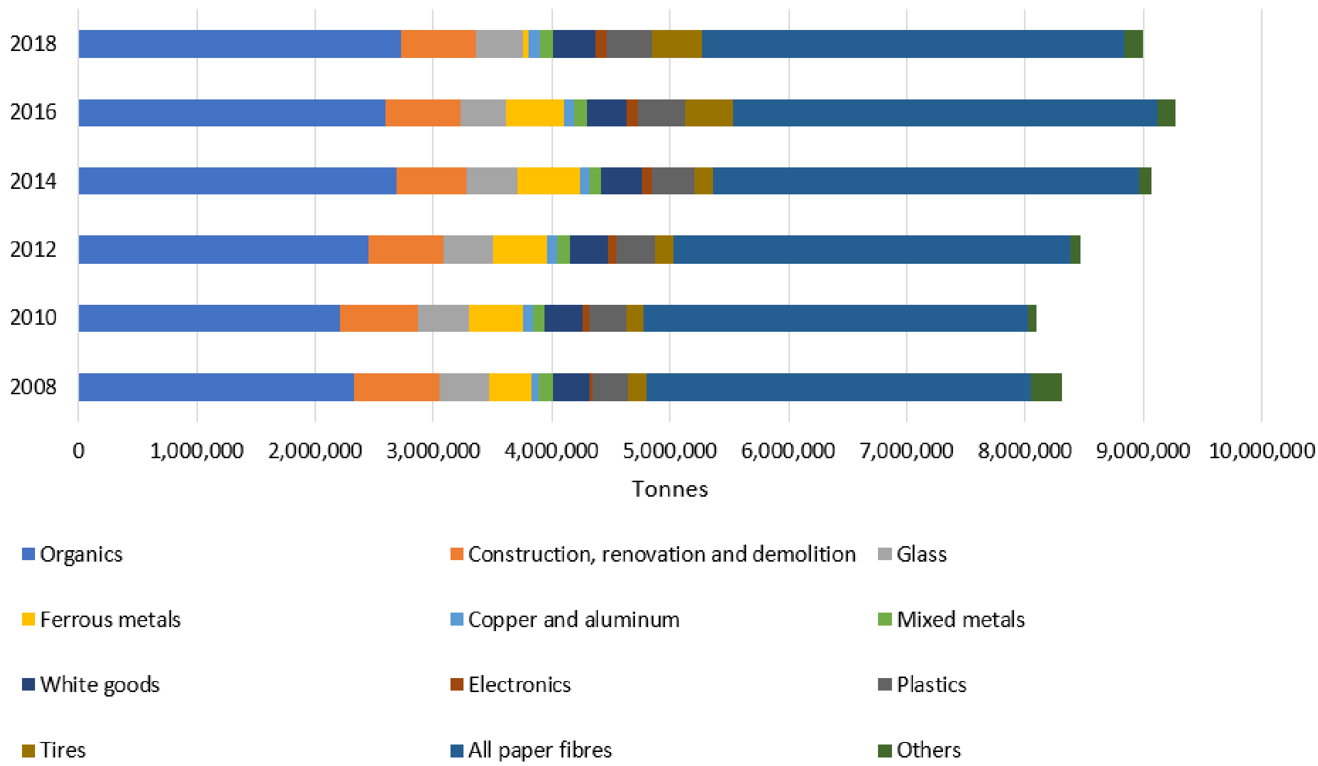

Figure 1. Materials prepared for recycling by companies and local waste management organizations in Canada. The authors originally produced the figure from Canada's national statistical agency [9].

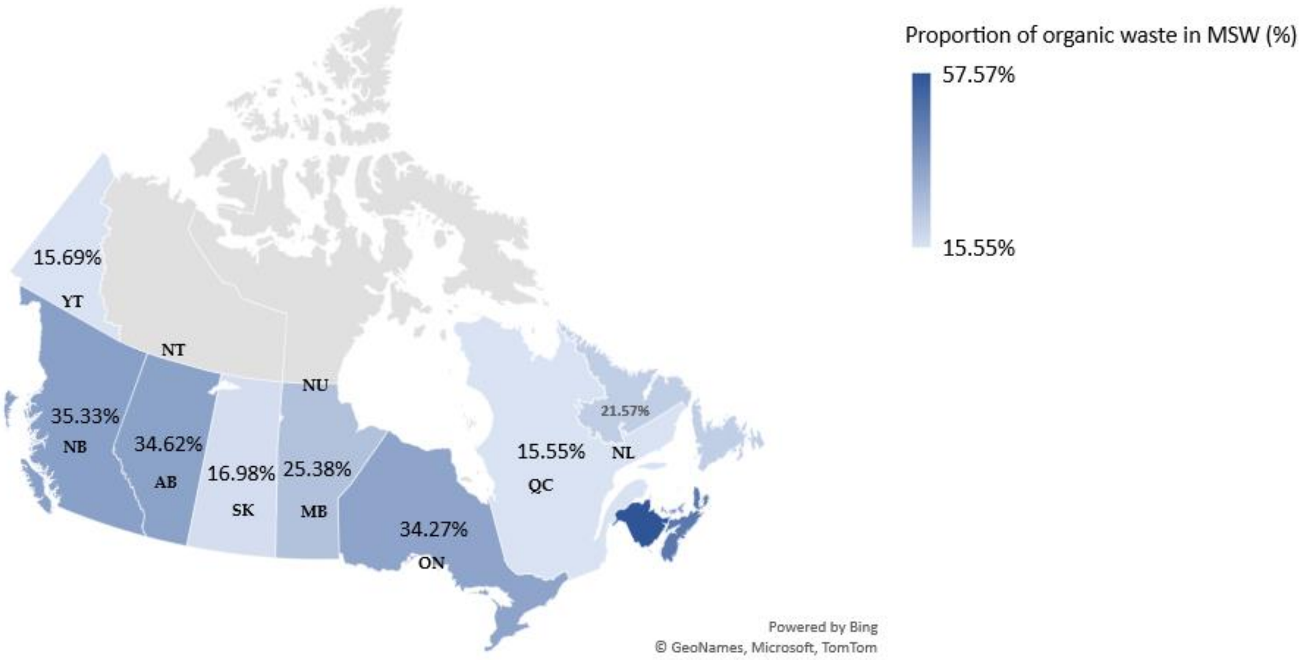

Figure 2. The proportion of organic waste diverted from municipal waste in Canada by province. The authors originally produced the figure from Canada's national statistical agency [9].

AD is a process by which organic waste streams produced in the food and beverage industry, the paper industry, agriculture, WWTPs, and households, are converted into biogas, liquid, and solid fertilizers, owing to the anaerobic bacteria or facultative anaerobic bacteria [12,13]. The largest bioenergy facility to manage OFMSW is the Rialto bioenergy facility implemented in North America. This plant can process 700 tonnes per day of organics from food waste and biosolids from WWTPs to produce renewable electricity to power the facility, export renewable electricity onto the grid, and export RNG to fuel their fleet of NG fueled vehicles. The plant is also able to produce class A fertilizer and soil conditioner [14]. At present, AD technology has been significantly advanced in Europe and turned into a well-established waste management strategy within the continent. With 18,943 biogas plants, 725 biomethane plants, 15.8 billion m^3 of biogas, and 2.4 billion m^3 of biomethane, Europe is considered the leading producer of biomethane [15]. However, compared with Europe, biogas production in Canada is a small but growing industry. Canada should reform its renewable energy policies and economic incentives to enter the league of biogas leaders. There are three reasons for today's fast-growing Canadian RNG marketplace. First, over 480,000 kilometres of natural gas pipelines are already available in Canada. Second, according to Ontario's FID program, the cost of the RNG project is lower than solar, wind, and biogas. Finally, RNG has a great production potential from Canadian organic waste streams [16–19].

To the best of our knowledge, this paper is the first review paper providing a guideline for better selecting OFMSW management methods. This review covers the technological advances in biogas plants, the composition of MSW by province, inventory of publicly owned solid waste assets, existing anaerobic digesters, the current Canadian policies that both encourage and enforce, and suggestions for building a zero organic waste future.

2. Policies/Regulations on AD in Both Recycling and Energy Recovery

Table 1 shows policies/regulations of 12 countries promoting AD for organic waste streams (particularly food waste and OFMSW). Regulations and policies on the treatment of organic waste streams are not yet uniform globally. However, protecting and preserving the environment is the priority in all laws and regulations. Biogas plants are becoming a popular waste management strategy in cities where organic wastes are separated from landfills [20,21]. Due to the European Union (EU) legislation, most countries in the EU have both OFMSW separation infrastructure and biogas plants. With 18,943 biogas plants, 725 biomethane plants, 15.8 billion m^3 of biogas, and 2.4 billion m^3 of biomethane, Europe is considered the leading biomethane producer [15]. To reach the global targets for reducing GHG emissions, the United States enacted new regulations and announced incentives to promote facilities for recovering energy and resources from OFMSW. Currently, the US has 236 facilities in the form of water resource recovery facilities (WRRFs), standalone digesters, and on-farm digesters. To date, the most enacted and potentially important policies are the US EPA Renewable Fuel Standard and California's Low Carbon Fuel Standard (LCFS) [22].

Table 1. Policies/regulations of 12 countries promoting AD for organic wastes. Copyright 2021 by Elsevier [22].

Country	Policy/Regulations	Incentives	AD Applications
Australia	The National Food Waste Strategy identified the role of AD in both recycling and energy recovery.	Support for installing small-scale AD technology.	• Majority operated by the water, agro-waste, or food processing industries, and number of plants accepting post-production FW is increasing. • Co-digestion of organic waste from commercial and industrial sources.
Canada	Policies to support RNG from AD.	Feed-in tariff (FIT) program resulted in 40 AD plants between 2010 and 2017 in Ontario.	• Few plants solely digest FW, or source-separated organics (SSOs). • Majority of plants co-digesting SSO with other feedstocks, most commonly agricultural manures at on-farm facilities, or less commonly with SS.
China	• China's medium- and long-term renewable energy plans of 2006 gave a target of 44 billion m^3 of biogas per year by 2020. • Mandatory garbage sorting for 46 cities.	Forcing the municipalities to resolve urban garbage problems increased number of AD installations.	• Mono FW digestion and co-digestion with other organic feedstocks.
Indonesia	The Ministry of Energy and Mineral Resources introduced favorable tariffs for electricity generated from municipal wastes and biomass.	Limited AD installations, especially for FW, although a number of initiatives, such as Indonesia Domestic Biogas program promoted AD for other feedstocks.	• Source segregated organics digestion in small-scale AD modelled on Indian designs; • Reusability of digestate is one of the main economic barriers.
United States	• The US EPA Renewable Fuel Standard; • California's Low Carbon Fuel Standard (LCFS); • Landfill bans in many states.	• RINs • Renewable electricity production tax credit • Carbon credits • Nutrient credits	• 236 facilities processing FW using AD; • Higher number of WRRFs processing FW, but standalone facilities process higher FW volume; • Tipping fees major source of revenue.
United Kingdom	• Waste Resources Action Program; • The Renewable Heat Incentive (RHI) program ends by 2021, but current UK policy on climate change and its Climate Change Act commitments can bridge the policy by 10–15%.	• The RHI • The Feed-In Tariff for renewable electricity.	• Approximately 8% of FW sent to AD • Gate fees for AD plants receiving FW fall from GBP 35 to GBP 11 per ton.

Table 1. *Cont.*

Country	Policy/Regulations	Incentives	AD Applications
Vietnam	• Little or no separate collection of FW; • No AD schemes have been applied to manage organic FW.	Strategies to 2025 focus on methods to recover energy and materials from MSW in cities.	FWs account for about 60%. The increasing rate of MSW annually is about 12%. However, currently, all 35 MSW treatment plants in Vietnam are using landfilling, incineration, or composting. Some recent studies have indicated that there is a very high potential in producing biogas via AD process from MSW in Vietnam.
Thailand	• AD of FW is not very common due to many operational issues; • Many pilot programs have been initiated, but most were unsuccessful or not sustainable.	Many pilot programs include small AD operations in urban and rural areas.	• Small-scale community/school AD operations suffer from operational and maintenance issues; • Co-digestion of household FW and waste from farm animals.
South Korea	• FW disposal into landfills was banned in 2005; • "Pay-as-you-throw" initiative helped tracking source-separated FW; • Bioenergy strategy has a target to increase biogas production by a factor of 4 by 2030.	The Ministry of Environment has also funded biogas Research on organic wastes to energy with a budget of USD 74 million from 2013 to 2020.	• Source segregated organics digestion in standalone digesters. • Co-digestion with animal manures and sewage sludges.
Singapore	The National Environmental Agency's pilot plan to co-digest FW with SS towards achieving energy neutrality in wastewater treatment.	The co-digestion pilot-scale program will be extended to all sewage treatment plants if it is successful.	• Majority of food waste is processed in incinerators; • Some small-scale community, university, and business AD operations.

China's long-term renewable energy plan, in 2006, aimed at producing 44 billion m^3 of biogas per year by 2020. This plan mandated municipalities to use mono and co-digestion of food waste with other organic feedstocks. They successfully implemented many biogas plants between 2006 and 2020. "Chongqing Black Stone Food Waste Treatment Plant", with a processing capacity of 365 thousand tonnes per year and biogas yield of 28 million m^3 per year, is one of the largest plants in China [5,15]. In the United Kingdom, due to the Waste Resources Action Plan and RHI, and FIT programs dedicated to improving renewable electricity, approximately 8% of food waste streams are sent to AD. Canada's policies for supporting AD-based systems are similar to the UK [23,24]. In Canada, the FIT program supports RNG from AD. This program resulted in the implementation of frothy AD plants between 2010 and 2017 across Canada. Some countries in Asia are also making great progress in shifting from conventional waste management systems to AD-based WWTPs. For example, Japan is one of the pioneers in developing AD facilities. They enacted a new law introducing AD as a promising method to reuse food waste. They installed the first biogas plant in 2000 when incineration was the dominant waste management method for resource recovery from MSW in Asia. In Japan, many food-based companies currently use anaerobic digestion to process food wastes (e.g., soy sauce and shochu by-products). The South Korean Ministry of Environment banned disposal into landfills and invested USD 74 million, from 2013 to 2020, on biogas research, to be able to combine co-digestion to all sewage sludge (SS) treatment plants industrially. The most commonly used feedstock in existing sewage treatment plants is animal manure. They are planning to increase biogas production by a factor of four by 2030.

As seen in Table 1, although the implementation of biogas plants in China, the US, Canada, UK, Japan, Australia, and South Korea was successful, some countries such as Thailand, Singapore, Malaysia, and Vietnam still have had problems commercializing the AD technology. This is technically due to the lack of source segregate collection infrastructure, weak national policies, expertise, and knowledge in the AD process. In

Singapore, the National Environmental Agency recently started investigating the feasibility of running co-digest food waste with SS to obtain energy neutrality in wastewater treatment. They plan to apply this approach to all sewage treatment plants if it is successful [22].

While AD is being implemented commercially in the EU, in Canada, AD projects still suffer a lack of infrastructure for SSO, management, and technical knowledge on the AD process. Herein, the importance of public–private partnerships is highlighted to show its vital role in creating a more stable revenue generation system and overcoming implementation challenges. Recent literature and governmental reports suggest that the following three factors are driving forces for shifting a country from conventional to AD based waste management strategies:

- Governmental incentives and discouragements (e.g., carbon credits, nutrient credits, and tipping fees major);
- Energy expense reductions (renewable electricity production tax credit, RHI, RIN, and FIT);
- Environmental benefits.

Although AD technology has been considered the best solution worldwide to achieve net-zero emissions by 2050, it still needs to be modified from the technical, market, economic, institutional, socio-cultural, and environmental points of view. Table 2 highlights challenges faced by the implementation of AD in various countries and the root cause of the problems in the implementation.

Table 2. Challenges faced by the implementation of AD in various countries. Copyright 2019 by Elsevier [25].

Barriers	Sub-Barriers
Technical	• Infrastructural challenges (e.g., plant size, lack of resource availability, limited number of gas filling stations); • Technical failures and problems and negative images caused by failed biogas plants; • Need for specialized technical staff and expertise (incl. a lack of technical training and knowledge); • Poor collection, improper segregation, a lack of vehicles, and adequate waste transportation; • Insufficient follow-up services; • Specific characteristics of biogas; • Dependency on imported materials.
Economic	• High investments/lack of available capital (low incomes and widespread poverty); • Lack of subsidies and financial support programs (incl. fossil fuel subsidization); • High cost of biogas production, transportation, clean-up, and upgrading; • Unavailability of bank loans (incl. with preferential terms); • Lack of R&D funding.
Market	• Lower prices of fossil fuels; • High price of biogas/ biomethane; • Competition with other fuels; • Easy availability of fuelwood at zero private cost; • Uncertainties related to the injection of biogas into the grid.
Institutional	• Lack of political support/legislation; • Uncertain policy landscape (incl. political instability); • Lack of private sector participation and poor coordination between the public and the private sectors; • High level of bureaucracy (e.g., complex administrative and legal procedures).

Table 2. *Cont.*

Barriers	Sub-Barriers
Socio-cultural	• Lack of public participation and consumer interest; • Desire to maintain the status quo/Resistance to change; • Low level of knowledge; • Lack of information and information sharing; • Lack of literacy rate/Low level of education; • Cultural and religious outlook including stigmatization; • Migration.
Environmental	• Odor complaints; • Noise complaints; • Need for abundant water resources for biogas digesters; • Lack of access to adequate water; • Pollution.

3. Canada's Existing Infrastructures for the Solid Waste Management

Figure 3 shows Canada's existing infrastructures for solid waste management. Seven types of waste management facilities are actively operating in Canada, which are transfer station assets, composting, material recovery facility, anaerobic digestion, engineered landfill, incineration, and energy from waste. As shown in Figure 3, Ontario, Quebec, Alberta, British Columbia, Newfoundland, Manitoba, and Saskatchewan adopted around 1813, 713, 1204, 581, 324, 595, and 1074 waste management facilities, respectively. Currently, the most common approach for municipal waste disposal in Canada is landfilling. Although modern MSW landfills are able to collect and treat leachate and capture greenhouse gasses, it is still not a suitable approach for the disposal of waste. Environmental analysis of incineration, gasification, AD, landfill, and composting showed AD has obvious advantages in the environmental criteria over other methods. Mondello et al. compared the potential environmental impacts of four waste management strategies—namely, landfill, incineration, composting, and AD, to manage organic waste, particularly food waste, using the life cycle assessment (LCA) method [26]. Based on the treatment of a functional unit of 1 tonne of food waste, the energy use in AD is lower than other options. In addition, the main environmental impacts were detected for landfill and incineration options, which is in agreement with the literature. Among studied strategies, AD showed the best environmental performance.

Reducing the amount of organic waste entering landfills is now a high priority worldwide. In Canada, the total amount of MSW diverted to recyclable materials (e.g., organics, plastics, tires, paper, electronics, etc.) increased from 8.3 million tonnes in 2008 to 9.8 million tonnes in 2018. The organic fraction of MSW has a great potential to be converted into renewable energies by AD or other waste-to-energy facilities. Thus, in recent years, Canada's MSW treatment plants are gradually adopting the AD mode of operation in which the OFMSW can be converted into biogas, electricity, and fertilizer. The two most populous provinces, Ontario and Quebec, recycled the most organics and implemented the highest number of AD plants in 2018, with 40 and 9 plants, respectively. In Ontario, such fast-paced green development is due to provincial incentives and discouragements such as the FIT program.

A higher number of waste-to-energy facilities was recorded in New Brunswick. In this province, over seven thousand tonnes of tires and organics are diverted from disposal. These materials are great input for thermochemical technologies such as pyrolysis and gasification. Plastic, in particular, has been the target material of recent programs such as the Federal Action Plan on Zero Plastic Waste. This program aims to reduce the presence of microplastics in oceans and mitigate its negative effect on the ecosystem and human health. British Columbia also recycles over 65 thousand tonnes of plastic, 42 thousand tonnes of tires, and 590 thousand tonnes of organics. With the current incentives and regulations, we can expect an increase in waste-to-energy capacity in the near future in British Colombia [27].

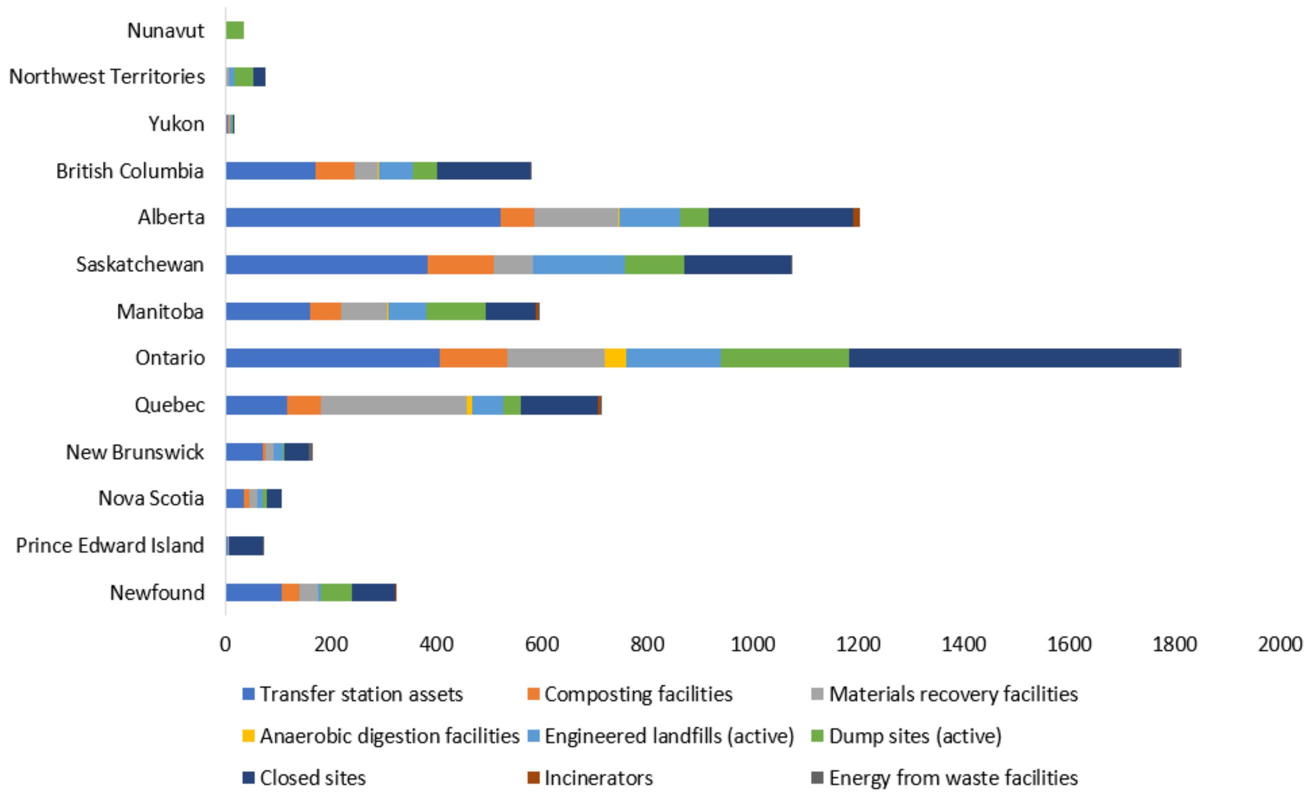

Figure 3. Public-owned MSW management infrastructures in Canada. The authors originally produced the figure from Canada's national statistical agency [28].

4. Biogas Projects in Ontario

Ontario government has been encouraging renewable natural gas (RNG) market in the province through updating its Climate Change Action Plan and founding biogas projects since 2016. Since then, AD has been extensively implemented, from pilot to industrial scale, in the form of WRRFs, standalone digesters, and on-farm digesters [28]. Table 3 shows existing biogas plants projects in Ontario for energy and resource recovery. The information on volume, organic input, and biogas plants' capacity was obtained from the Canadian Biogas Association, Canada's national statistical agency, and manufacturer websites. As can be seen, most biogas plants in Ontario are operating to process agricultural wastes and the manure produced by cattle in farms. Among them, Delft Blue Veal Inc. (Cambridge), Koskamp Family Farms (Stratford), Athlone BioPower (Tavistock), and Donnandale Farms (Stirling) have the highest capacity (≈2000 m^3) and can generate 500 kW of electricity. Some AD plants were installed in different locations for the purpose of training students and farmers. The most famous one is CARES located at the University of Guelph Ridgetown Campus. This biogas plant consists of a 1527 m^3 digester to process dairy and swine manure and crude glycerol to generate 250 kW of electricity. In addition to pilot-scale AD plants, a few cities in Ontario (i.e., Toronto, Bridgeport, and Surrey) are using large-scale AD plants to extract energy and resources from MSW. The biggest project is related to the Dufferin Organics Processing Facility (DOPF) in Toronto. With a high capacity of 55,000 tonnes per year, this facility converts SSO collected annually in the residential and commercial Green Bin Program into electricity. City of Surrey's Organic Waste Biofuel Processing Facility converts the city's MSW into RNG and supplies waste collection and recycling vehicles fuels. County of Oxford has been using Ingersoll WWTP anaerobic digester since 2011. The facility consists of two identical digesters (two-phase AD), with a volume of 1090 m^3 for each digester, and is fed only by waste-activated sludge (WAS).

Table 3. Several biogas plants projects in Ontario for energy and resource recovery. The table was originally produced by the authors from the information shared by the Canadian Biogas Association [29].

Technology	Source	Type	Description	Location
CCI Disco	Source separated organics (SSOs) collected in the residential and commercial Green Bin Program	Single phase	Biogas is used to provide heating for the facility and for the functioning of the anaerobic digestion system and upgraded to renewable natural gas and injected into Ontario's natural gas grid. Digester solids are sent to a composting facility in southern Ontario.	City of Toronto
Dufferin Organics Processing Facility (DOPF.)	Source separated organics (SSOs) collected annually in the residential and commercial Green Bin Program	Single phase	The original DOPF, which had been built to process 25,000 tonnes of organic material annually from the City's Green Bin Program, will be upgraded with new processes and expanded to a capacity of 55,000 tonnes per year.	City of Toronto
Bridgeport Wastewater Treatment Plant	Source-separated organic materials from commercial generators.	Single phase	The anaerobic digestion facility will generate over 10 million kWh of renewable electricity per year–enough to power more than 1000 homes.	City of Bridgeport
Surrey's Organic Waste Biofuel Processing Facility	City's solid waste Stream	Single phase	The system converts organic wastes into renewable natural gas (RNG) for waste collection and recycling vehicles.	City of Surrey
Ingersoll WWTP anaerobic digester	Waste activated sludge (WAS)	Two phase	The anaerobic digestion facility consists of a primary anaerobic digester with an operating volume of 1090 m^3 and a secondary anaerobic digester of identical capacity.	County of Oxford
ZooShare Biogas	Zoo manure and food waste	Single phase	The plant is designed to handle 17,000 tonnes of organic waste and recover 500 kW electricity.	Toronto
Escarpment Renewables	High total solids organic waste	Two phase	The plant is capable of producing 12,000 m^3 of biogas per day.	Grimsby
CARES—University of Guelph Ridgetown Campus	Farmer waste streams, manure, and glycerol obtained from biodiesel plants	Single phase	The AD is connected to a 250 kW MAN engine with an operating volume of 1527 m^3. The plant is built for training students and farmers.	Guelph
StormFisher	Farmer waste streams, manure, organic material, and mixed food scraps	Single phase	StormFisher is built to process 65,000 tonnes of organic wastes into electricity and fertilizer granules.	London
The Gardiner Farms	Farmer waste streams, manure, and organic material	Single phase	The Gardiner Farms produces electricity and thermal energy using two 250 kW CHP units.	Caledon
Greenholm Farms	Recycled digestate solids, organic waste, and the manure produced by cattle	Single phase	The plant is designed with an operating volume of 2077 m^3 and is able to produce 250 kW of energy.	Embro
Escarpment Renewables	Fats, oils, grease, and organic liquids	Single phase	Escarpment Renewables is an industrial AD facility that is permitted to receive 23,000 tonnes of organics annually.	Beamsville
Bayview Flowers Ltd.	Manure, grape pumice, corn silage, pet food	Single phase	The plant is designed with an operating volume of 1200 m^3 and its biogas is sent to a 250 kW Scania generator and a retrofitted boiler.	Jordan
Delft Blue Veal Inc.	Calf manure and discarded organic residuals provided by food processing companies	Single phase	The plant is designed with an operating volume of 1750 m^3 and is able to produce 499 kW of electricity.	Cambridge

Table 3. *Cont.*

Technology	Source	Type	Description	Location
Koskamp Family Farms	Manure and other organic materials	Single phase	The plant is designed with an operating volume of 1500 m^3 and is able to produce 500 kW of electricity.	Stratford
Athlone BioPower	Manure and other organic materials	Two phase	The facility has two anaerobic digesters, a primary and secondary tank, with an operating volume of 2077 m^3 in size for each of them. The plant is able to produce 500 kW of power.	Tavistock
Birchlawn Farms	On-farm materials and outsourced organic waste from food processing plants	Single phase	The plant is designed with an operating volume of 1800 m^3 and is able to produce 440 kW of electricity.	Listowel
Woolwich Bio-en Inc.	Food waste	Single phase	The facility is built to process 70,000 tonnes per year of organic wastes into electricity and fertilizer granules. The CHP's produce 2.852 MW of electricity under a Feed-in Tariff contract with the Ontario Power Authority.	Elmira
Chatsworth/Georgian Bluffs	Biosolids, grease trap waste, source-separated organics, and other organics	Two phase	The anaerobic digester is a two-stage process with a 100 m^3 hydrolysis tank and a 1000 m^3 digester.	Owen Sound
Clovermead Farms	Manure and other organic materials	Single phase	A 1500 m^3 anaerobic digester which supplies fuel for the 250 kW generator, installed by European Power Systems Ltd.	Aylmer
Marl Creek Renewables	Manure, milk, fats, oils, and grease	Single phase	The plant is designed with an operating volume of 4200 m^3 and is able to fuel two 250 kW combined heat and power units.	Elmwood
CCS agriKomp	Manure from the farm's beef herd, silage, crop residues, and FOG	Single phase	The plant is designed with an operating volume of 680 m^3 and is able to supply fuel for a 100 kW engine.	Millbrook
Donnandale Farms	Manure and other organic materials	Single phase	The plant is designed with two anaerobic digesters (1600 m^3 each) and is able to supply fuel for the 500 kW MWM generator.	Stirling

Most AD plants in Canada are single-phase AD, due to this method's simple design and process control. All four hydrolysis, acidogenesis, acetogenesis, and methanogenesis steps are carried out in a single digester. These types of ADs are usually applied for agricultural wastes consisting of materials resistant to ADs such as cellulose, hemicellulose, and lignin. However, as shown in Table 3, two-phase ADs are designed and implemented for easily biodegradable feedstock (e.g., biosolids, grease trap waste, source-separated organics, and other organics). These materials undergo fast-rate hydrolysis and acidogenesis, which, in turn, lead to the inhibition of methanogenesis by volatile fatty acids (VFAs) accumulation. Ingersoll WWTP anaerobic digester, Athlone BioPower, and Georgian Bluffs have two-phase AD digesters. The advantages of two-phase AD over single-phase AD are as follows:

i. Generation of both methane and hydrogen;
ii. Operational conditions and reactions can be easily controlled;
iii. Improving the speed limiting reaction (hydrolysis);
iv. Higher energy capacity.

Although most AD references in Canada are available in Ontario, there are some innovative AD projects in other provinces [30]. For example, a complete system to process high-strength brewery wastewater from a new Molson–Coors brewery was implemented in Longueuil (Montreal), Quebec, Canada. This unit can produce biogas up to 8450 Nm^3/d, including 72% of CH_4, which is equivalent to 3350 kg/day of fuel oil. Biogas generated in this unit is used to heat the inlet wastewater to maximize the anaerobic treatment efficiency and reduce energy costs. In British Columbia, a high-efficiency biogas plant coupled with a water wash biogas upgrading plant has been recently implemented in Metro Vancouvers Lulu Island WWTP. This unit is able to treat up to 800 Nm^3/h of raw biogas to RNG. Upgraded RNG is injected into the FortisBC gas grid [31].

5. Pretreatment Methodologies to Enhance OFMSW Biodegradability

With the development of biogas plants in the past several decades, pretreatment technologies have also gained momentum and have been successfully applied to stabilize and enhance methane production. As shown in Table 4, pretreatment technologies can be categorized into five types: mechanical, thermal, chemical, biological, and additives (hybrid) [32]. Since the OFMSW composition is relatively complex, the hydrolysis step is considered a rate-limiting phase among the four phases of hydrolysis, acidogenesis, acetogenesis, and methanogenesis. The main goal of pretreatment technologies is to promote the hydrolysis step [33–35].

As for mechanical pretreatment, some technologies are commercially available. The OREXTM (A patented press extruder) is capable of recovering over 90% of putrescible organics from mixed waste streams. Organic pulp extracted from the press extrusion process is highly degradable in AD processes. Disc screen process is another pretreatment method widely used in waste processing facilities. The process separates waste into unders containing putrescible organics and overs including coarse recyclables [36]. Thermal pretreatment is the process in which MSW is heated in the range of 100 °C. The process is performed using pyrolysis, hydrothermal carbonization (HTC), hydrothermal liquefaction (HTL), and microwave reactors. Although this method can increase methane yield, remove odor, and improve dewaterability, it is considered an energy-intensive method. High energy demand and capital cost of building and operating thermal systems become obstacles for their practical commercialization [37]. Chemical pretreatment is divided into three types: acidic, alkali, and ozonation, which relies on hydrolysis of hemicellulose, saphonication, and hydroxyl radicals, respectively. Chemical pretreatment is currently being used in full-scale operations in excess sludge reduction in WWTPs [38].

Regarding biological pretreatment, TPAD and MEC are the most widely used methods in promoting the AD process. In the TPAD method, hydrolysis and acidogenesis steps occur in the first tank under thermophilic conditions, and acetogenesis and methanogenesis in the second tank under mesophilic conditions. Two-stage biogas plants can result in increased methane yield, low energy demand, and better solid destruction. TPAD process offers lower VFAs, COD, and suspended solids concentrations in the effluent and higher methane yield [32].

Additives (e.g., zeolite, biochar, bricks, plastic beads, coconut coir, charcoal, $G_{AC,}$ etc.) have gained significant attention due to their ability in facilitating the adsorption of inhibitors, increasing buffering capacity, microbial growth, DIET, H_2S removal, and CO_2 sequestration. For example, zeolite can stabilize the process due to its cation exchange property via ammonia detoxification. Porous materials such as biochar, hydrochar, and GAC are natural molecular sieves and catalysts; thus, they can purify biogas by separating H_2S and CO_2 from CH_4 and N_2 [39].

In the above paragraphs, mechanical, thermal, biological, and physical pretreatment methods were comprehensively introduced and discussed. However, it is worth mentioning that there are only a few references worldwide applying such pretreatment methods. This is mostly due to technical, energy, economic and environmental barriers. Mainardis et al. have recently could develop a reliable and standard protocol based on physicochemical characterization, experimental tests, LCA, and economic analysis to determine the up-scale feasibility of the proposed pretreatment method for AD of sewage sludge. They investigated six different pretreatment technologies: thermal, alkali, combined alkali–thermal, ultrasonication, icing–thawing, and biochar addition. Among the proposed methods, in terms of biomethane potential, low-temperature thermal pretreatment (110%), ultrasonication (53%), and biochar addition (16%) showed the best performance. Figure 4 compares the LCIA results of ultrasonic, thermal, and biochar scenarios with the baseline scenario. In most environmental criteria, proposed pretreatment methods showed better performance. However, the economic analysis showed that the capital costs of these methods could not be recovered in 15 years only if we consider heat recovery for thermal pretreatment and lower price for the biochar addition scenario [11]. We believe that the current protocol is a robust tool to assess a proposed pretreatment technology from the technical, energy, economic and environmental points of view within the Canadian context.

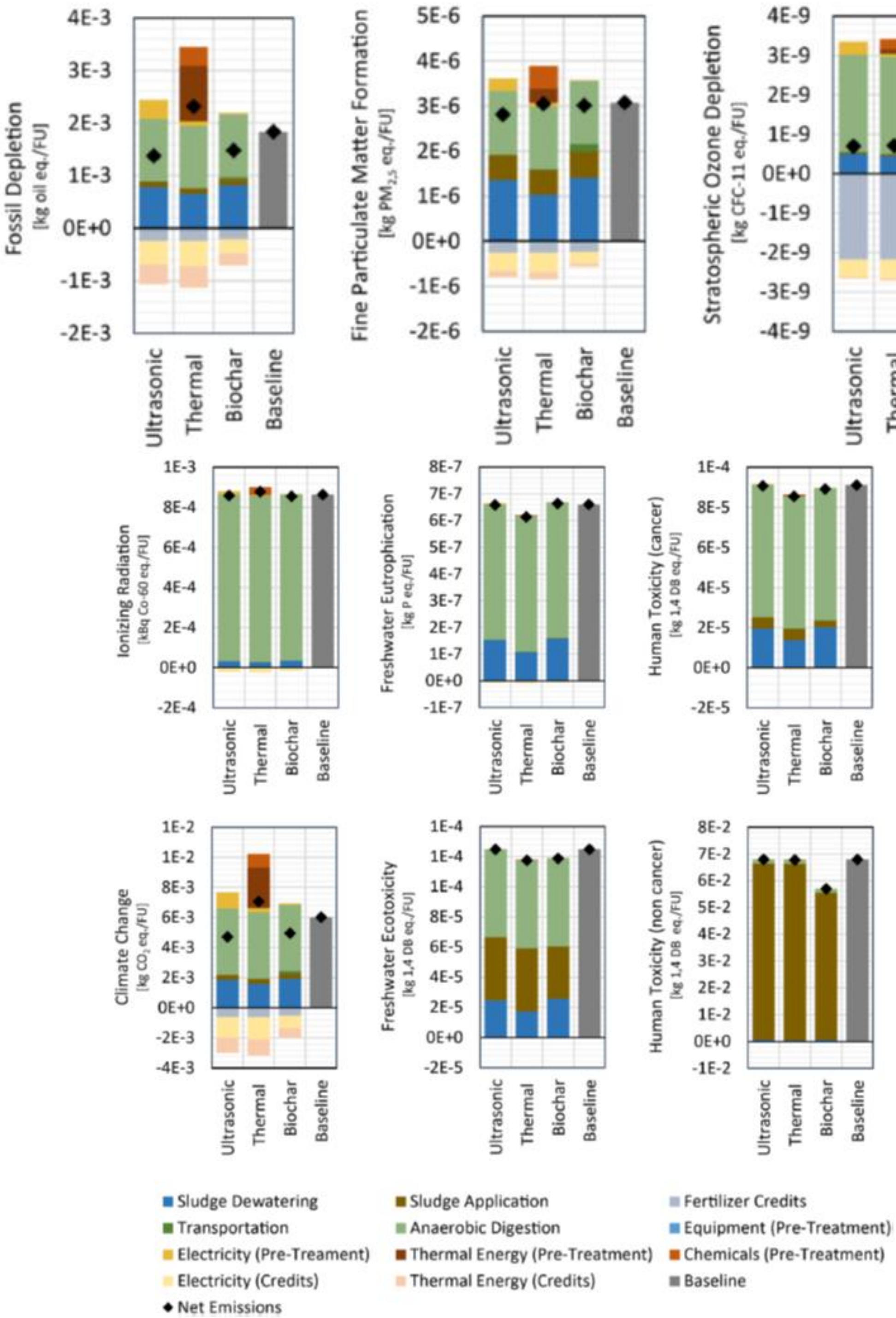

Figure 4. Comparison of ultrasonic, thermal, and biochar LCIA results with the baseline scenario at an industrial scale. Copyright 2021 by Elsevier [11].

Table 4. Summary of available commercial pretreatment AD technologies along with their advantages and disadvantages.

Pre-Treatment	Description	Available Processes	Advantages and Disadvantages	Commercial Technologies	Ref.
Mechanical treatment	Shredding and chopping of raw substrates to enhance the interaction between microorganisms and fragmented organic molecules (e.g., sugar, amino, and fatty acids)	• Press extruder • Disc screen • Bag opener • Wind sifter • High-pressure homogenizer • Sonication • Maceration	• Enhancement of COD solubilization • Improving nutrient availability to microbes • Excessive shredding or chopping of raw substrates may lead to the increased VFAs and inhibition of the AD process • Operational and capital cost is high	• OREX™ • Db-Disc Screen • Db-Wind Sifter • CleanREX™ • BIOREX™	[36]
Thermal treatment	Applying heat to decompose MSW via different approaches	• Hydrothermal • Microwave	• Removing pathogen • Enhancing the dewaterability properties • Polarization of macromolecules • Energy intensive • Treatment at high temperatures (>170 °C) lead to the complex recalcitrant substrates	• Patented Anaergia pyrolysis • CambiTHP™ • Biothelys® • Exelys, • Turbotec • Lysotherm, • Biorefinex	[32,40]
Chemical treatment	Chemical treatment is applied to disrupt the cell walls using strong and concentrated chemicals	• Commercial alkaline materials (e.g., NaOH and $CaCO_3$) • Ozone (O_3) • Peracetic acid • Acetic acid	• Easy operation • Suitable for lignin decomposition • Corrosion • Special materials for reactor construction, • Neutralization before digestion	• Full-scale operations in existing WWTP	[38]
Biological treatment	Promoting microbial growth	• Temperature phased anaerobic digestion (TPAD) • Microbial electrolysis cell (MEC)	• Eco-friendly • Low energy input • Operating at room temperature • Operational and capital cost is low		[32]
Additives	Additives can promote the AD process through adsorption of inhibitors, increasing buffering capacity, and microbial cell immobilization.	• Activated carbon • Biochar • Hydrochar • Conductive materials	• Adsorbing inhibitors such as LCFA, ammonia, limonene, heavy metals, and phenols. • Supporting microbial metabolism • Buffering pH during hydrolysis and acidogenesis steps • Contributing to the circular economic approach • Direct Interspecies Electron Transfer (DIET)		[39,41]

6. Guideline for Better Selection of OFMSW Management Methods

Over the past 10 years, Canada has been investigating the feasibility of various available renewable energy sources such as biomass, wind, and solar. The challenge is to achieve net-zero emissions by 2050 [24,42,43]. As discussed before, many incentives and regulations have been passed to support RNG. These incentives are increasing exponentially in terms of both values and numbers, according to a bench analysis in Canada. Among the solutions for climate change, RNG could be considered a negative carbon fuel. However, other solutions can reduce GHG emissions maybe by 40% in the best-case scenario, and they can not reach net-zero emissions. The cost of large and small scale RNG, biogas, solar, and wind power projects offered by Ontario's feed-in-tariff (FIT) program were estimated by Canadian Gas Association. The average price in 2008 was CAD 8/GJ and has fallen in recent years to CAD 3/GJ due to robust supplies of natural gas. More information on the affordability of natural gas prices can be found here [19]. The lower project cost of RNG and the existing NG pipeline infrastructure are the main reasons for today's fast-growing Canadian RNG marketplace.

Some robust, cutting-edge solutions for OFMSW recovery from MSW in Canada are available. Unlike traditional approaches, these solutions can recover 90% of organics without limitations on in-feed contamination levels. OFMSW is a nutrient-rich feed for AD and can be used in co-digestion plants to increase biogas production. Figure 5 shows the process of waste sorting and recovery in treatment facilities. The OREX^{TM} can separate the OFMSW through a high-pressure extrusion process. The organic fraction is used in the advanced anaerobic digestion process to produce methane-rich biogas and, in turn, electricity, fertilizer, and clean water. In order to convert organic waste into biogas and fertilizer, there are three advanced options—namely, single-phase, two-phase, and high-solid digesters. A single-phase digester is designed for readily biodegradable substrates such as food waste. However, a two-phase digester is ideal for materials needing both primary and secondary fermentation, such as energy crops. The double-ring tank provides two-stage digestion in a decreased footprint.

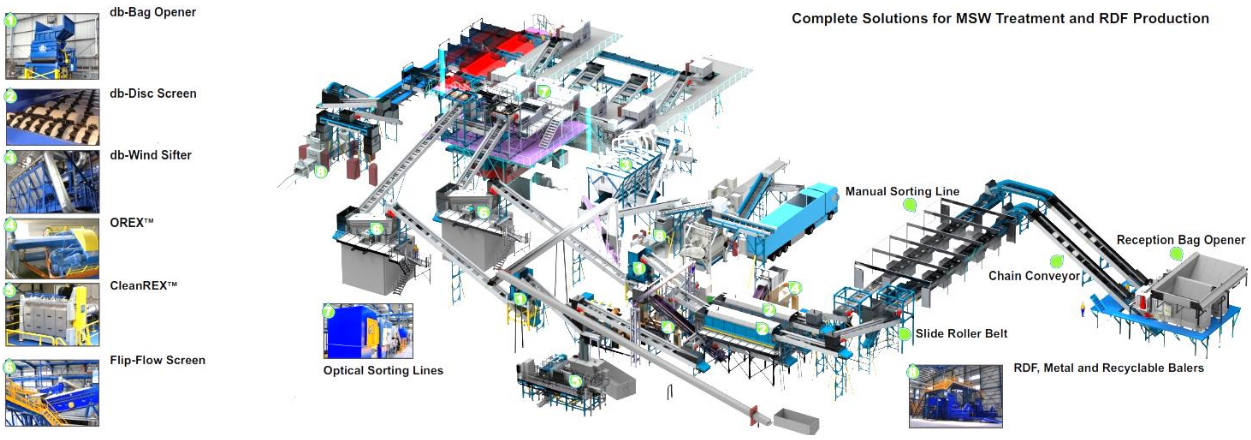

Figure 5. Recovering organics and recyclables from MSW and wet commercial waste. The authors originally produced the figure.

Single- and two-phase digesters can be converted into high-solids digesters using solid Omnivore^{TM} technology to significantly increase capacity and biogas production. The main advantages of a high-solid digester are as follows:

- It transforms municipal WRRFs for co-digestion and works towards energy neutrality;
- It enables reception and co-digestion of high strength waste streams such as fats, oils, and grease, or the organic fraction from municipal waste;
- It reduces foaming potential with high torque mechanical mixing.

Although AD technology is receiving increasing attention due to government incentives and public support, there is still significant room for increasing AD performance via integrating the produced biogas with other renewable energy sources. For example, in WRRFs, anaerobic digesters could be coupled with photovoltaic energy generation, wind turbines, and battery storage, potentially creating a 100% renewable WRRF. Campana et al. developed a model and applied it to a medium-scale Italian municipal WWTP. They also analyzed the costs of installing and operating proposed renewable scenarios [44].

Another important by-product alongside biogas that should be considered in the anaerobic treatment of OFMSW is digestate. Currently, the main focus of Canadian project developers and policymakers is on financial subsidies coming from RNG production. They do not consider the market opportunities of digestate in the agricultural application (i.e., organic fertilizer) and the non-agricultural applications (i.e., soil remediation, biochar production, landfill cover, and landscape restoration). In line with the concept of circular economy, European Commission has specified certain principles to collect revenue from OFMSW digestate. Beggio et al. have recently statistically analyzed the quality of digestate from OFMSW and agro-industrial feedstock. The results suggest that digestate derived from OFMSW could be considered for direct agricultural use as fertilizer. However, it is worth mentioning that the feasibility of using OFMSW digestate should be further investigated by considering hygiene features and ecotoxicological thresholds. This approach is being introduced in other developed countries, including Canada. Policymakers are working on national regulations defining digestate quality to ensure the economic viability and environmental safety of OFMSW digestate use [45]. The most successful reference of using OFMSW digestate as class A fertilizer is the Realto bioenergy facility in California, United States. This facility has the capacity to receive 700 tonnes per day pre-processed SSO and 300 tons per day dewatered WWTP sludge and convert them into 3 MW electricity, 1200 standard, cubic feet per minute RNG, and 26 tonnes per day biochar.

In Canada, to involve stakeholders in AD projects, a national AD guideline document has been developed by the Canadian Biogas Association (CBA) [46]. The guideline includes the following features:

- Best planning, design, and operational practices to assist stakeholders (i.e., project developers, regulators, organizations);
- Recommendations supporting the circular economy concept;
- A clear outline to assist stakeholders in converting food and organic waste streams using AD.

7. Conclusions

Detailed information on the proportion of organic waste diverted from MSW and recent Canadian regulations and incentives enable decision makers to select the best strategies for waste management. The FIT program shifted the conventional waste management strategies to highly integrated biogas production strategies between 2010 and 2017, particularly in Ontario. However, to reach the global Paris Agreement and join leading countries in biogas production, Canada should focus more on the reform of renewable energy policies and economic incentives. The introduction of OFMSW into the cities existing WWTPs provides significant opportunities for Canada's renewable energy market. However, more studies are needed on pretreatment technologies to generate more biogas and accomplish a better rate of organic decomposition to make the process more effective and economically feasible. Most digesters in Ontario work at low volume (1000 to 2000 m^3) and generate 100–500 kW of electricity for being used on-site. The province has only a capacity of around 100 AD facilities that convert organic waste into biofuels, biopower, and bioproducts. Incineration still is the most widely used technology for resource recovery from MSW. Considering how the biogas industry has evolved in Europe, it can be concluded that the biogas industry growth in Canada relies on (1) provincial energy and waste management policies; (2) using advanced technologies for diverting organic waste from landfill; (3) improving biogas yield using existing pretreatment methods; (4) educating farmers regarding digester operations. Future studies in the field should focus on obtaining a 100% renewable energy system and reducing capital investment cost via developing a novel energy system integrating photovoltaic, wind turbine generation, hydrogen, and battery storage.

Author Contributions: Conceptualization, O.N.; methodology, O.N.; software, O.N.; validation, O.N. and A.D.; investigation, O.N.; resources, A.D.; writing—original draft preparation, O.N.; writing—review and editing, A.D. and O.N.; visualization, O.N.; supervision, A.D.; project administration, A.D.; funding acquisition, O.N. and A.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Ministry of Agriculture, Food and Rural Affairs grant number [HQP2019-1592 Project] And Biomass Canada of BioFuelNet Canada Network [Project Number: ASC-16].

Institutional Review Board Statement: Not applicable.

Acknowledgments: The authors would like to express their sincere gratitude to Sasha Rollings-Scattergood, VP Technology at Anaergia, for their helpful advice and support.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

Organic fraction municipal waste	OFMSW	Renewable heat incentive	RHI
Anaerobic digestion	AD	Source-separated organics	SSOs
Feed-in tariff	FIT	California's Low Carbon Fuel Standard	LCFS
Renewable natural gas (NRG)	RNG	Dufferin Organics Processing Facility	DOPF
European Union (EU)	EU	Food waste	FW
Municipal solid waste	MSW	Sewage sludge	SS
Water resource recovery facilities	WRRFs	Microbial electrolysis cell	MEC
Temperature-phased anaerobic digestion	TPAD	Direct interspecies electron transfer	DIET
Hydrothermal carbonization	HTC		

References

1. Parizeau, K.; von Massow, M.; Martin, R. Household-level dynamics of food waste production and related beliefs, attitudes, and behaviours in Guelph, Ontario. *Waste Manag.* **2015**, *35*, 207–217. [CrossRef]
2. Parizeau, K.; von Massow, M.; Martin, R.C. Directly observing household food waste generation using composition audits in a Canadian municipality. *Waste Manag.* **2021**, *135*, 229–233. [CrossRef]
3. Babu, R.; Veramendi, P.M.P.; Rene, E.R. Strategies for resource recovery from the organic fraction of municipal solid waste. *Case Stud. Chem. Environ. Eng.* **2021**, *3*, 100098. [CrossRef]
4. Parvez, A.M.; Lewis, J.D.; Afzal, M.T. Potential of industrial hemp (*Cannabis sativa* L.) for bioenergy production in Canada: Status, challenges and outlook. *Renew. Sustain. Energy Rev.* **2021**, *141*, 110784. [CrossRef]
5. Negri, C.; Ricci, M.; Zilio, M.; D'Imporzano, G.; Qiao, W.; Dong, R.; Adani, F. Anaerobic digestion of food waste for bio-energy production in China and Southeast Asia: A review. *Renew. Sustain. Energy Rev.* **2020**, *133*, 110138. [CrossRef]
6. Zubi, G.; Dufo-López, R.; Carvalho, M.; Pasaoglu, G. The lithium-ion battery: State of the art and future perspectives. *Renew. Sustain. Energy Rev.* **2018**, *89*, 292–308. [CrossRef]
7. Janus, A. More Than Half of All Food Produced in Canada is Lost or Wasted, Report Says. CBC News. Available online: https://www.cbc.ca/news/canada/toronto/food-waste-report-second-harvest-1.49817282019 (accessed on 6 January 2022).
8. Di Maria, F.; Sordi, A.; Micale, C. Energy production from mechanical biological treatment and Composting plants exploiting solid anaerobic digestion batch: An Italian case study. *Energy Convers. Manag.* **2012**, *56*, 112–120. [CrossRef]
9. Canada, S. Table 38-10-0034-01 Materials Diverted, by Type, Inactive. Available online: https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3810003401 (accessed on 6 January 2022).
10. Canada, S. Table 38-10-0033-01 Materials Diverted, by Source, Inactive. Available online: https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3810003301 (accessed on 6 January 2022).
11. Mainardis, M.; Buttazzoni, M.; Gievers, F.; Vance, C.; Magnolo, F.; Murphy, F.; Goi, D. Life cycle assessment of sewage sludge pretreatment for biogas production: From laboratory tests to full-scale applicability. *J. Clean. Prod.* **2021**, *322*, 129056. [CrossRef]
12. Norouzisafsari, O.; Di Maria, F.; El-Hoz, M. A short review of comparative energy, economic and environmental assessment of different biogas-based power generation technologies. *Energy Procedia* **2018**, *148*, 846–851. [CrossRef]
13. Di Maria, F.; Sisani, F.; Norouzisafsari, O.; Mersky, R.L. The effectiveness of anaerobic digestion of bio-waste in replacing primary energies: An EU28 case study. *Renew. Sustain. Energy Rev.* **2019**, *108*, 347–354. [CrossRef]
14. Adam Redling Anaergia Begins Construction of North America's Largest WTE Facility. WasteToday 2018. Available online: https://www.wastetodaymagazine.com/article/anaergia-rialto-waste-to-energy/ (accessed on 6 January 2022).
15. Jin, C.; Sun, S.; Yang, D.; Sheng, W.; Ma, Y.; He, W.; Li, G. Anaerobic digestion: An alternative resource treatment option for food waste in China. *Sci. Total Environ.* **2021**, *779*, 146397. [CrossRef]
16. FortisBC Energy Inc. *Renewable Natural Gas Supplier Guide*; FortisBC Energy Inc.: Columbia, Canada, 2018; p. 14.
17. Studies, C. Case Studies Surrey, British Columbia Saint-Hyacinthe, Quebec. 2017. pp. 1–4. Available online: https://biogasassociation.ca/resources/rng_outreach_and_market_development (accessed on 6 January 2022).
18. Audrey. The Renewable Natural Gas Quality Specifications in North America. American Gas Association 2010, pp. 5–7. Available online: https://www.aga.org/research/reports/renewable-natural-gas-rng/ (accessed on 6 January 2022).

19. Canadian Gas Association. *Renewable Natural Gas Technology Roadmap for Canada*; Canadian Gas Association: Ottawa, ON, Canada, 2014; p. 24.
20. Pognani, M.; Barrena, R.; Font, X.; Sánchez, A. A complete mass balance of a complex combined anaerobic/aerobic municipal source-separated waste treatment plant. *Waste Manag.* **2012**, *32*, 799–805. [CrossRef] [PubMed]
21. Alibardi, L.; Cossu, R. Composition variability of the organic fraction of municipal solid waste and effects on hydrogen and methane production potentials. *Waste Manag.* **2015**, *36*, 147–155. [CrossRef] [PubMed]
22. Dalke, R.; Demro, D.; Khalid, Y.; Wu, H.; Urgun-Demirtas, M. Current status of anaerobic digestion of food waste in the United States. *Renew. Sustain. Energy Rev.* **2021**, *151*, 111554. [CrossRef]
23. Zachary, A. Anaerobic digestion can help UK reach renewable energy targets. *Renew. Energy Focus* **2016**, *17*, 21–22. [CrossRef]
24. Ackrill, R.; Abdo, H. On-farm anaerobic digestion uptake barriers and required incentives: A case study of the UK East Midlands region. *J. Clean. Prod.* **2020**, *264*, 121727. [CrossRef]
25. Nevzorova, T.; Kutcherov, V. Barriers to the wider implementation of biogas as a source of energy: A state-of-the-art review. *Energy Strat. Rev.* **2019**, *26*, 100414. [CrossRef]
26. Mondello, G.; Salomone, R.; Ioppolo, G.; Saija, G.; Sparacia, S.; Lucchetti, M.C. Comparative LCA of Alternative Scenarios for Waste Treatment: The Case of Food Waste Production by the Mass-Retail Sector. *Sustainability* **2017**, *9*, 827. [CrossRef]
27. Canada, G. of Zero plastic waste: Canada's actions Canada-wide Strategy on Zero Plastic Waste. Available online: https://www.canada.ca/en/environment-climate-change/services/managing-reducing-waste/reduce-plastic-waste/canada-action.html (accessed on 6 January 2022).
28. Canadian Biogas Association. *RNG Outreach and Market Development*; Canadian Gas Association: Ottawa, ON, Canada, 2017.
29. Canadian Biogas Association. *Biogas Projects in Canada*; Canadian Gas Association: Ottawa, ON, Canada, 2019; pp. 2–3.
30. Canadian Biogas Association. *Current Status and Future Potential of Biogas Production from Canada's Agriculture and Agri-Food Sector*; Canadian Gas Association: Ottawa, ON, Canada, 2018.
31. Biogas World Biogas and Biomethane Projects. 2021. Available online: https://www.biogasworld.com/news/showcase-report-2021-is-out/ (accessed on 6 January 2022).
32. Zhen, G.; Lu, X.; Kato, H.; Zhao, Y.; Li, Y.-Y. Overview of pretreatment strategies for enhancing sewage sludge disintegration and subsequent anaerobic digestion: Current advances, full-scale application and future perspectives. *Renew. Sustain. Energy Rev.* **2017**, *69*, 559–577. [CrossRef]
33. Pagés-Díaz, J.; Pereda-Reyes, I.; Taherzadeh, M.J.; Sárvári-Horváth, I.; Lundin, M. Anaerobic co-digestion of solid slaughterhouse wastes with agro-residues: Synergistic and antagonistic interactions determined in batch digestion assays. *Chem. Eng. J.* **2014**, *245*, 89–98. [CrossRef]
34. Dong, L.; Zhenhong, Y.; Yongming, S. Semi-dry mesophilic anaerobic digestion of water sorted organic fraction of municipal solid waste (WS-OFMSW). *Bioresour. Technol.* **2010**, *101*, 2722–2728. [CrossRef] [PubMed]
35. Ji, C.; Kong, C.-X.; Mei, Z.-L.; Li, J. A Review of the Anaerobic Digestion of Fruit and Vegetable Waste. *Appl. Biochem. Biotechnol.* **2017**, *183*, 906–922. [CrossRef] [PubMed]
36. Anaergia Municipal Solid Waste-Anaergia's Approach for Waste Revalorization. 2021. Available online: https://www.anaergia.com/what-we-do/municipal-solid-waste/materials-recovery (accessed on 6 January 2022).
37. Norouzi, O.; Taghavi, S.; Arku, P.; Jafarian, S.; Signoretto, M.; Dutta, A. What is the best catalyst for biomass pyrolysis? *J. Anal. Appl. Pyrolysis* **2021**, *158*, 105280. [CrossRef]
38. Akbay, H.E.G.; Dizge, N.; Kumbur, H. Enhancing biogas production of anaerobic co-digestion of industrial waste and municipal sewage sludge with mechanical, chemical, thermal, and hybrid pretreatment. *Bioresour. Technol.* **2021**, *340*, 125688. [CrossRef] [PubMed]
39. Chiappero, M.; Norouzi, O.; Hu, M.; Demichelis, F.; Berruti, F.; Di Maria, F.; Mašek, O.; Fiore, S. Review of biochar role as additive in anaerobic digestion processes. *Renew. Sustain. Energy Rev.* **2020**, *131*, 110037. [CrossRef]
40. Ghysels, S.; Acosta, N.; Estrada, A.; Pala, M.; De Vrieze, J.; Ronsse, F.; Rabaey, K. Integrating anaerobic digestion and slow pyrolysis improves the product portfolio of a cocoa waste biorefinery. *Sustain. Energy Fuels* **2020**, *4*, 3712–3725. [CrossRef]
41. Arif, S.; Liaquat, R.; Adil, M. Applications of materials as additives in anaerobic digestion technology. *Renew. Sustain. Energy Rev.* **2018**, *97*, 354–366. [CrossRef]
42. Medrano, J.; Llosa-Tanco, M.; Cechetto, V.; Tanaka, D.A.P.; Gallucci, F. Upgrading biogas with novel composite carbon molecular sieve (CCMS) membranes: Experimental and techno-economic assessment. *Chem. Eng. J.* **2020**, *394*, 124957. [CrossRef]
43. Stephen, J. Renewable Natural Gas (Biomethane) Feedstock Potential in Canada. 2020. Available online: https://www.enbridge.com/~{}/media/Enb/Documents/Media%20Center/RNG-Canadian-Feedstock-Potential-2020%20(1).pdf?la=en (accessed on 6 January 2022).
44. Campana, P.E.; Mainardis, M.; Moretti, A.; Cottes, M. 100% renewable wastewater treatment plants: Techno-economic assessment using a modelling and optimization approach. *Energy Convers. Manag.* **2021**, *239*, 114214. [CrossRef]
45. Beggio, G.; Schievano, A.; Bonato, T.; Hennebert, P.; Pivato, A. Statistical analysis for the quality assessment of digestates from separately collected organic fraction of municipal solid waste (OFMSW) and agro-industrial feedstock. Should input feedstock to anaerobic digestion determine the legal status of digestate? *Waste Manag.* **2019**, *87*, 546–558. [CrossRef]
46. Ellis, D. Canadian Anaerobic Digestion Guideline. 2019; pp. 1–76. Available online: https://biogasassociation.ca/resources/canadian_anaerobic_digestion_guideline (accessed on 6 January 2022).