energies

Article

The Current Status and Lost Biogas Production Potential of Kazakhstan from Anaerobic Digestion of Livestock and Poultry Manure

Dulatbay Yerassyl [1,2], Yu Jin [1,*], Sugirbaeva Zhanar [3], Kazambayeva Aigul [2] and Yessengaliyeva Saltanat [2]

[1] College of Economics and Management, Northwest A&F University, Xianyang 712100, China; eros.kz@nwafu.edu.cn
[2] Department of Science, Zhangir Khan West-Kazakhstan Agrarian-Technical University, Uralsk 090009, Kazakhstan; aigul-km@wkau.kz (K.A.); salta-em@wkau.kz (Y.S.)
[3] Department of Higher Mathematics, L.N. Gumilyov Eurasian National University, Nur-Sultan 010000, Kazakhstan; sugirbayeva_zht@enu.kz
* Correspondence: yujin@nwsuaf.edu.cn; Tel.: +86-136-3021-2958

Abstract: Kazakhstan has large reserves of natural resources, including coal, oil, and natural gas. We hope to replace fossil fuels with renewable sources of energy—particularly renewable natural gas. Thus, Kazakhstan, like other countries, should cut its dependency on coal, oil, and natural gas so as to reach net zero carbon emissions by 2050. This study, given that Kazakhstan is an agricultural country with a large amount of organic matter, analyzes the potential of biogas production as a source of electricity and heat. Manure from livestock and poultry was chosen as a source of organic matter. The climate of Kazakhstan in most of its territory is sharply continental, with large temperature differences, which affect the process of anaerobic digestion. Consequently, the features of biogas production in cold regions were analyzed, and the calculation shows that the equivalent of 27,723,802 kWh of calorific energy could be obtained from the anaerobic digestion of livestock and poultry manure, while the annual energy consumption of Kazakhstan was 9423 billion kWh. Moreover, a policy is suggested to develop biogas production in Kazakhstan based on the agricultural land distribution among farmers.

Keywords: biogas; methane; livestock manure; anaerobic digestion; organic matter

check for updates

Citation: Yerassyl, D.; Jin, Y.; Zhanar, S.; Aigul, K.; Saltanat, Y. The Current Status and Lost Biogas Production Potential of Kazakhstan from Anaerobic Digestion of Livestock and Poultry Manure. *Energies* **2022**, *15*, 3270. https://doi.org/10.3390/en15093270

Academic Editor: Attilio Converti

Received: 21 March 2022
Accepted: 27 April 2022
Published: 29 April 2022

1. Introduction

Kazakhstan possesses an abundance of natural resources, including coal, oil, natural gas, and uranium, and has significant renewable energy potential from wind, solar, hydro, and biomass. Using fossil fuels changes the regime of temperature, and the precipitation regime caused by GHG emissions has a significant impact on people and their activities, as well as the distribution of vegetation and soil development [1,2]. To reduce energy dependence on fossil fuels and greenhouse gas emissions in accordance with the obligations of the Paris Agreement, concept of the transition of the Republic of Kazakhstan to a green economy by 2050 was developed and put forward [3]. Due to the size of the country's territory, geography, and economic structure, the distribution of electricity in Kazakhstan is not uniform, causing the rural and remote areas to experience a serious electricity deficit [4]. Hence, renewable energy resources such as solar, wind, and biomass, which are available in abundance in Kazakhstan, should be actively and urgently promoted. The usage of renewable energy decreases dependency on fossil fuels, mitigates climate change, conserves natural resources, and provides the potential for local economic development through job and small business creation [5]. If not considering the climatic conditions, biogas technology can be more suitable than other renewable technologies, particularly because of three reasons: Firstly, biogas technology is relatively simple, and operates on both small and large scales [6–9]. Secondly, biogas technology can replace traditional biomass fuel for cooking and the generation of electricity [10,11]. Thirdly, biogas technology transforms organic matter into organic fertilizer without causing harm to the atmosphere. Here, we have to mention that during the production of mineral fertilizers and organic fertilizers, significant amounts of carbon dioxide (CO_2) and GHGs are emitted into the atmosphere [12,13]. The efficiency of the farm starts from growing forage for ruminants. The question is how efficiently we are using land, and how much forage we are growing. There is also the critical question of whether the farmer applies mineral fertilizers or organic fertilizers into the soil. First of all, using mineral fertilizers to increase the yield is an expense for farmers. Not applying mineral fertilizers reduces soil humus and leads to a low yield. Nevertheless, the production of mineral fertilizers causes air and soil pollution. Supposing that farmers can efficiently use natural resources such as cattle manure to obtain organic fertilizer as well as biogas, the farmer's income is supplemented not only by the purchase of milk and meat, but also from the processing of manure.

Agricultural waste is a term for all organic matter that remains after harvesting and processing crops to produce certain agricultural products, as well as organic matter left over from animal husbandry. The main share of agricultural waste in Kazakhstan is as follows:

- Cultivation of crops: Collection and processing of wheat, barley, and sugar beet. Typical waste types include stems, straw, leaves, husks, cake, roots, etc.
- Livestock: Breeding of pigs, cows, horses, chickens, and other animals. Typical waste types include slurry, animal manure, animal wastewater, silage, slaughter waste, litter residues, etc.

The aim of this research is to determine the potential of biogas production from livestock and poultry manure, despite the existence of other organic matter resources, because there is a lack of information on the types of organic matter villagers are producing. In this research, the total livestock and poultry manure are calculated based on the number of livestock and poultry in Kazakhstan by region. However, it should be noted that the potential of biogas production in Kazakhstan is assessed only by the presence of livestock and poultry manure.

2. Materials and Methods

2.1. Area of Study and Challenges to Overcome

Using grassland resources reasonably, alleviating grassland degradation, and improving the grassland ecosystem services are challenges to Kazakhstan's production of livestock resources [14,15].

The area of Kazakhstan is divided into 14 regions (Table 1). The population of Kazakhstan is 18,631,800 people, where 58.7% live in 87 cities, while the remainder live in the 30 settlements and 6454 villages. Kazakhstan is a Central Asian country with steppe and pastures in the north, deserts and semi-deserts in the center and the western basins of the Caspian and Aral Seas, and mountains in the Tien Shan and Pamir ranges. Agricultural land totals 76.5 million hectares, of which 61% is permanent pasture and 32% is arable land, where grain and livestock are grown [16]. The climate of Kazakhstan is continental; it is characterized by intensely cold winters, with January air temperatures ranging from −18.5 °C in the north of the country to −1.8 °C in the south, and hot summers, with July air temperatures ranging from 19.4 °C in the north to 28.4 °C in the south [17]. Despite the cold weather conditions, small- and large-scale biogas plants are operational in Kazakhstan [18]:

- One of the most successful projects for generating electricity from organic waste in Kazakhstan was implemented at a distance of 7 km from the village of Kogershin in the Zhambyl region. There is a pig-breeding complex with an area of 30 ha. The daily productivity of biogas is 5300 m^3 per day;
- In the Kostanay region, on the territory of the Karaman-K farm, a biogas plant has been operating since 2011. All equipment for the production of biogas and electricity was designed and supplied by "Zorg Biogas Ukraine". The biogas plant, consisting of 2 reactors of 2400 m^3 each, has been brought to full capacity, and generates 360 kW of

electrical power. Annually it is expected to produce 3 million kWh of electricity from biogas. There are about 5000 cows on the farm;

- In the East Kazakhstan region, in the village of Privolnoye, a biogas plant operates on the basis of the Bagration farm, which allows the processing of 10 tons of manure per day and produces 400 m^3 of gas;
- In the Aktobe region, in the village of Sazdy, a biogas plant operates on the Bolashak farm, and produces 2 m^3 of biogas per day.

Table 1. Administrative–territorial structure of Kazakhstan in 2021 [19].

Regions	Territory, Thousand km^2	Districts	Cities	Settlements	Villages
Akmola	146.1	17	10	5	602
Aktobe	300.6	14	8	-	344
Almaty	223.6	17	10	-	732
Atyrau	118.6	7	2	-	159
Western Kazakhstan	151.3	12	2	3	435
Zhambyl	144.3	10	4	-	373
Karaganda	428.0	11	11	10	421
Kostanay	196.0	16	5	3	548
Kyzylorda	226.0	7	4	2	232
Mangystau	165.6	5	3	-	58
Pavlodar	124.8	10	3	4	354
North Kazakhstan	98	13	5	-	649
Turkestan	116.1	13	7	-	836
East Kazakhstan	283.2	15	10	3	711

2.2. Biogas Production Features in Cold Regions

The biogas production process and various methods depending on available organic matter quantity are well explained in the literature [20–22]. However, there is an issue with biogas production in cold regions. Temperature plays a crucial role in anaerobic digestion, as it shapes microbial ecosystems and, therefore, regulates the stability of the anaerobic digestion process [23]. In cold regions, biomethanation processes with efficient substrate composition, insulation, psychrophilic anaerobes, reactor systems, and additives are some advanced approaches that can improve biomethanation [24] (Figure 1).

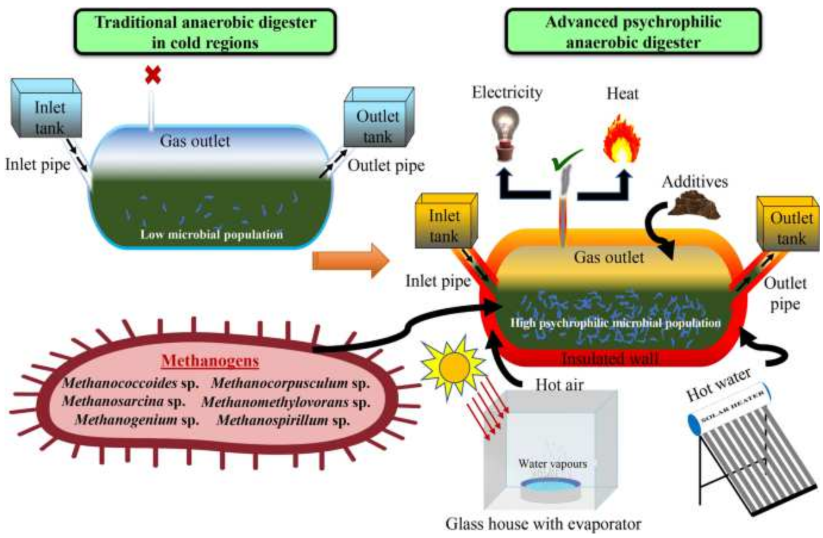

Figure 1. Features to improve biomethanation under low temperatures. Reprinted from Manyapu, Kumar [24].

The mixture of the suitable organic substrate plays a major role in the production of biogas via anaerobic digestion. For example, improved biogas production compared to mono-digestion of guinea pig manure alone is found in the higher altitudes of the Andes Mountains, where the cow manure is co-digested with guinea pig manure [25]. Moreover, methane generation was found to double when the urine and dung of dairy cows were digested with the fish silage as a co-substrate at 10 °C, compared to the digestion of cow dung and urine alone, in Norway [26]. Another experiment showed more biogas production at 16.6 °C when the cow and sheep manure were mixed compared to cow manure alone [27].

For higher biogas production via psychrophilic biomethanation, the digestion system must be aided with adequate insulation techniques to maintain mesophilic conditions. Solar heating is considered to be an efficient and economical method for insulation, as demonstrated in Latin-American regions [28]. The hot water released from an electrical generator using biogas produced from anaerobic digestion of manure can be utilized to insulate the digester [29]. The heat generated in the nearby greenhouse can insulate the digester, where the warm air source is pumped into the digester to increase the inside temperature and establish mesophilic conditions [30]. Moreover, a low-cost, small-scale digester can be covered with a greenhouse made of PVC to capture solar heat [31].

In addition to maintaining a comfortable temperature, the role of the cold-adapted microbial community in the efficient production of methane is clear. Due to the ability to utilize both acetoclastic and hydrogenotrophic pathways, *Methanosarcina* sp. significantly dominated *Methanosaeta* sp., and proved to be effective in the process of biomethanation inside an anaerobic membrane bioreactor [32]. *Methanococcoides* sp., *Methanomethylovorans* sp., and *Methanosarcina* sp. produce methane through both hydrogenotrophic and acetoclastic processes [33].

The additives also help to retain heat and maintain the required temperature inside the anaerobic digester to increase microbial activity, resulting in higher methane production at low temperatures. Wheat straw and barley straw are used as additives in combination with organic substrates such as cow dung and pig manure for enhancing psychrophilic biomethanation [34,35]. When biochar was added at 10 g/L to an anaerobic digester with dairy manure, the methane yield increased by 26–28% [36]. The addition of granular activated carbon to the anaerobic digestion of municipal wastewater stimulated the development of potential microorganisms, resulting in the production of large amounts of methane [37].

2.3. Agricultural Land Distribution

The amount of agricultural land possessed by the farmers is more significantly influenced by economic competition in producing animal feed than by purchasing in the market. The production of biogas is increased by increasing the production of animal feed [38]. Therefore, the amount of agricultural land possessed by farmers and the amount of animal manure, depending on manure type, should be analyzed.

2.4. Calculation of Approximate Amounts of Produced Livestock and Poultry Manure

The production of biogas and methane was calculated in each region. In this study, the approximate amount of produced livestock and poultry manure was calculated as follows [39]:

$$TM_i = N_i \times AAW_i \times MPC_i \quad (1)$$

where TM_i is the total manure produced in one year (kg), N_i is the number of animals, AAW_i is the weight of the adult animal (kg), and MPC_i is the manure production coefficient, which can be obtained from Table 2. The standard deviation of AAW_i and MPC_i was not taken into account, as it depends on feeding conditions and feed quality [40].

Table 2. Weights and manure production coefficients for different adult animals [41–44].

	AAW (kg) Adult Animal Weight	*MPC* Manure Production Coefficient	Q_{AM} (kg) Approximate Annual Manure Produced
Cattle	350	3.65	2226.5
Sheep and goats	70	3.36	235.2
Horses	454	3.2	5040
Pigs	50	5.7	720
Poultry	1.6	4.4	7.04
Camels	600	2.6	952

Manure from various animals has various specific capabilities in biogas and methane production. The produced amount of biogas depends not only on the amount of organic matter, but also on the type of organic matter. The amount of produced biogas, depending on organic matter type, is calculated as follows [39]:

$$PB_i = TM_i \times BA_i \tag{2}$$

where BA_i is the biogas amount (m^3/kg) (Table 3).

The carbon dioxide (CO_2) and other undesirable gases are separated from the produced biogas to obtain methane (CH_4), and the methane rate also varies depending on organic matter type [45]. Therefore, it is necessary to analyze not only the amount of organic matter, but also the amount of methane production. The amount of the methane in the produced biogas is calculated as follows:

$$MA_i = PB_i \times MR_i \tag{3}$$

where MR_i is the methane amount (m^3) (Table 3).

Table 3. Biogas and methane produced from different manures [46–49].

	Produced Biogas Amount, (m^3/kg)	Methane Rate	CO_2 Rate
Cattle	0.26–0.28	0.5–0.6	0.4–0.5
Sheep and goats	0.22–0.24	0.4–0.5	0.6–0.5
Horses	0.16–0.21	0.5–0.65	0.35–0.5
Pigs	0.3–0.4	0.6–0.7	0.3–0.4
Poultry	0.4–0.6	0.5–0.7	0.3–0.5
Camels	0.2–0.25	0.55–0.65	0.35–0.45

The production of biogas from organic matter via anaerobic digestion is one side of the coin, and the recovery of methane from biogas by employing upgrading technologies is the other [50]. Methane should be separated from the biogas. If not separated, each cubic meter of biogas contains the equivalent of 6 kWh of calorific energy. However, when we burn biogas for electricity, about 2 kWh of useable electricity is obtained, and the rest is converted into energy that can be used for heating [51].

3. Results and Discussion

3.1. The Analysis of Livestock and Poultry Distribution in Kazakhstan

The numbers of livestock and poultry are not uniformly distributed in Kazakhstan, and depend on the weather conditions (Table 4). For example, most populations of camels are kept only by farmers in areas with low precipitation and sandy soils, such as Atyrau, Aktobe, Kyzylorda, Mangystau, and Turkestan. Figure 2 shows the numbers of livestock and poultry in Kazakhstan at the end of 2019. After poultry, sheep and goats are the second most abundant. The number of cattle is about three times the number of horses.

However, the produced animal waste depends on animal size. Bigger animals produce more agricultural waste.

Table 4. The numbers of livestock and poultry in Kazakhstan at the end of 2019, by region [52].

Regions	Numbers of Livestock and Poultry, Thousands					
	Cattle	Sheep and Goats	Pigs	Horses	Camel	Poultry
Akmola	434	535.2	99	202.1	0.1	8014.2
Aktobe	493.5	1127.1	58.4	144.3	17.8	1320.9
Almaty	1028.1	3511.8	53.3	327	7.4	10,311.2
Atyrau	173.4	567.6	0.4	83.9	32.5	455.6
Western Kazakhstan	591.5	1130.6	17.3	192.8	2.2	1442.8
Zhambyl	423.2	2861.8	20.9	136	6.9	1702
Karaganda	549.2	924.5	72.2	337.2	1.4	4080.8
Kostanay	462.4	463.6	165.8	122.9	0.2	4269
Kyzylorda	332.4	620.9	2.6	148.3	47.9	127.2
Mangystau	22	422.5	0.1	86.5	68.8	43.3
Pavlodar	426.6	551.6	73.7	184.6	0.1	1695.8
North Kazakhstan	365.5	419.3	173.9	130.9	0	4617.1
Turkestan	1052.9	4291.2	6.6	346.4	30.4	2175.4
East Kazakhstan	1004.5	1611.6	65.2	394.5	0.6	3877.8

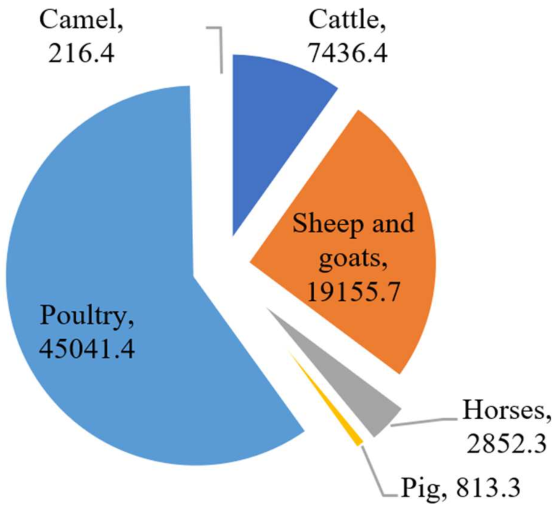

Figure 2. The numbers of livestock and poultry in Kazakhstan at the end of 2019 (thousands) [52].

3.2. Analysis of Agricultural Land Distribution

To keep livestock and poultry, farmers need agricultural land to grow the animals' food. However, the agricultural land is not distributed equally, requiring farmers without land to purchase animal food. If farmers own little agricultural land, they grow forage crops, compared with the farmers who own vast agricultural land and grow cereals crops to export. However, if farmers keep livestock and poultry depending on their agricultural land area, the farmers who own vast areas of agricultural land have significant opportunities to produce manure. According to Figure 3, the agricultural land is not standardized; it is normally distributed to the peasants or farm enterprises—10,740 peasants or farm enterprises possess 28,529,178 hectares, while 82,807 peasants or farm enterprises possess 991,885 hectares. This means that 7.8% of peasants or farm enterprises possess 57.6% of agricultural land, while 60.6% of peasants or farm enterprises possess 2% of agricultural land. The vast majority of agricultural land is separated from 1000 hectares to 10,000 hectares, while the vast majority of peasants or farm enterprises possess less than 50 hectares. The farmers who own vast agricultural land could construct biogas plants if keeping livestock and poultry depends on agricultural land size. We consider that this should be controlled by policy, as even the cereals grown by farmers to export as crop residues can be used to feed animals, as can spent mushroom compost after harvesting mushrooms. The crop residues are rarely fed to animals, as this is less productive. However, agricultural waste is a resource for growing mushrooms. The spent mushroom compost is used as animal feed, feedstock for biogas production, and fertilizer [53,54]. Consequently, if considering 1000 hectares to be vast agricultural land, 19,261 farmers could construct biogas plants. It should be noted that in Kazakhstan the population living in villages does not need agricultural land to keep livestock, because every village has common land to graze their livestock. However, there is a norm of pasture area per head of farm animals on restored and degraded lands—from 8 to 30 hectares, depending on the type of animal [55,56]. In North Kazakhstan, the harsh winter does not allow grazing for livestock. Therefore, the presence of agricultural lands to gather animal food is necessary. Nevertheless, the farmers who own little agricultural land and/or farmers without agricultural land who purchase animal food, in the event of the construction of a biogas plant nearby, could sell the manure of their livestock or poultry. Therefore, we consider that the policy should encourage farmers to build biogas plants, as 117,338 farmers own less than 500 hectares of agricultural land. The lack of knowledge in commercializing AD technology and weak national policy has been noted as a problem in other countries [57].

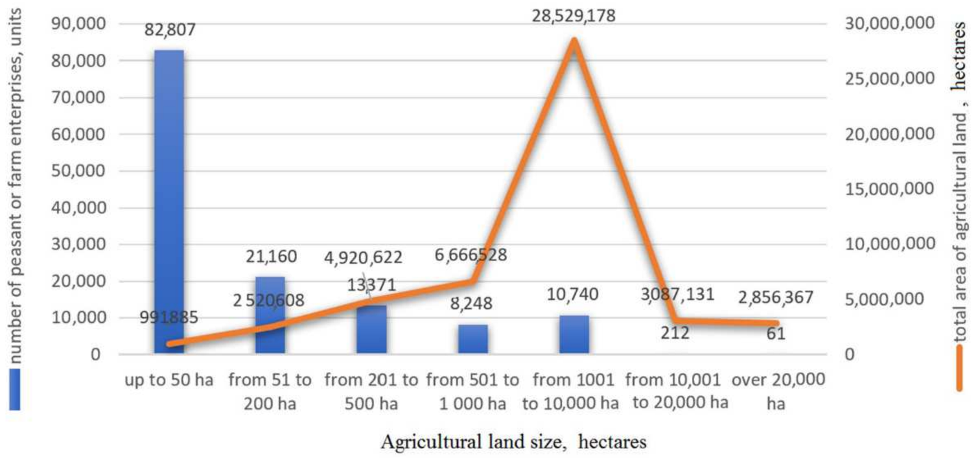

Figure 3. The number of peasant or farm enterprises and the total area of agricultural land possessed in 2019 [52].

3.3. Livestock and Poultry Manure Production Results

The production of cattle manure prevails in all regions, except for the Zhambyl region, where sheep and goat manure occupy first place, and the production of cattle manure comes second (Figure 4). The production of sheep and goat manure takes second place in the Aktobe, Almaty, Atyrau, and Turkestan regions. In other regions, the production of horse manure takes second place. In the Aktobe, Atyrau, Mangystau, and Turkestan regions, the production of camel manure prevails over the production of poultry manure. The approximate manure production from cattle, sheep and goats, horses, camels, poultry, and pigs was 9,401,378 kg, 4,478,043 kg, 4,122,174 kg, 337,428 kg, 310,697 kg, and 230,679 kg, respectively. It should be noted that manure production depends on the age of the animals. However, manure calculations were based on the average productivity of adult animals, since no other information was available beyond the number of adult animals in Kazakhstan. Moreover, there is also a lack of information on how farmers keep their livestock. If livestock grazes on pastures, manure is lost [58]. However, this research studies the possibility of future biogas production from manure in the event that biogas plants are constructed and the farmers decide to keep their livestock on farms. Otherwise, the production of biogas via anaerobic digestion in Kazakhstan is not possible.

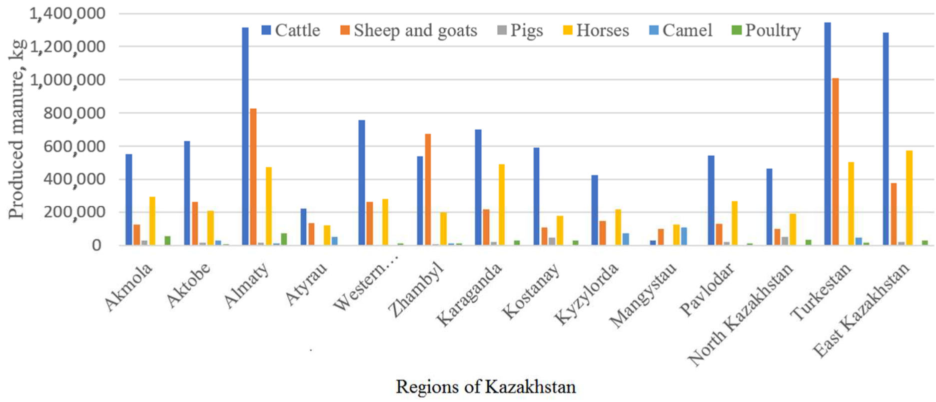

Figure 4. Produced manure in Kazakhstan by region in 2019.

3.4. The Results of the Assessment of Methane Production

It is considered that methane production depends on the animal manure type and methane rate. However, according to Figure 5, the difference between the animal manure type and methane volume has an insignificant effect compared with the animal manure amount, as the tendency of methane amount and produced manure is similar. The production of methane from poultry and pig manure would be more efficient, as they produce twice the amount of biogas produced from other animal manure (Table 3). Nevertheless, the poultry and pig manure are not the main organic source. The cattle, sheep, and goat manure are the most promising organic manures for producing biogas in Kazakhstan. However, to produce biogas, any type of manure can be the source of organic matter. Therefore, overall, 2,495,006 m^3 of methane or 4,620,633 m^3 of biogas could be produced if the livestock and poultry manure were processed via anaerobic digestion in Kazakhstan. Nevertheless, the equivalent of 27,723,802 kWh of calorific energy would be obtained, while the annual energy consumption of Kazakhstan is 9423 billion kWh. It should be noted that the production of biogas or methane was calculated based on the production of manure from adult animals and the average value of the methane rate.

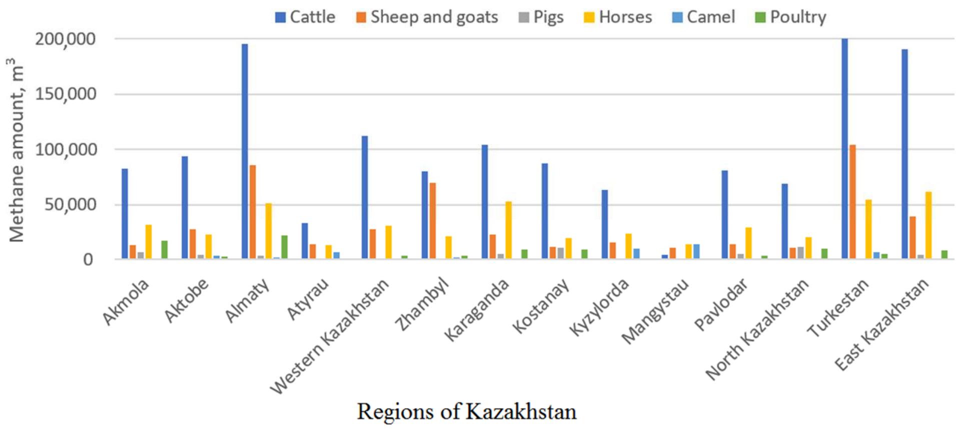

Figure 5. Amount of methane production in Kazakhstan in 2019.

4. Conclusions

Organic matter is the basic source to produce biogas in biogas plants via anaerobic digestion. Kazakhstan has plenty of livestock and poultry manure to produce biogas. However, this potential is not fully utilized, as the livestock manure is not collected to produce biogas, due to a lack of knowledge of AD technology, along with weak government policy. The analysis shows that Kazakhstan lacks biogas plants has only several biogas plants. However, there is a dramatic opportunity to produce biogas if farmers who own vast agricultural land have the potential to construct biogas plants suitable for the cold regions. Therefore, a law should be enacted to allow farmers to keep livestock and poultry relative to the size of their agricultural land, regardless of the purpose of the agricultural land. Farmers with small agricultural holdings can collect or sell livestock and bird manure if a biogas plant is built nearby. If the total potential for biogas production was exploited, the equivalent of 2,772,380,283 kWh of energy would be obtained. The annual energy consumption of Kazakhstan is 9423 billion kWh. Comparatively the potential energy production from biogas would account for only 3% of the total annual energy consumption of Kazakhstan. However, this energy would be enough to cook and to heat houses in the remotely located villages. According to the analysis, cattle, sheep, and goat manure are promising organic matter sources for producing biogas.

Author Contributions: Conceptualization, D.Y. and S.Z.; methodology, S.Z. and K.A.; software, Y.S.; validation, D.Y.; formal analysis, Y.S.; project administration, Y.J.; funding acquisition, Y.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (grant number 71874139) and the Ministry of Science and Technology of the People's Republic of China (grant number 2017YFE0181100).

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors appreciate the administrative and technical support provided by Sugirbay Adilet and English language editing by Fatima Duisebayeva.

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

References

1. Spiridonov, V.; Ćurić, M. Climate and Climate Change. In *Fundamentals of Meteorology*; Springer: Cham, Switzerland, 2021; pp. 377–397.
2. Kenenbayev, S.B.; Yesenbayeva, G.L. Adaptation of priority research direction in agriculture to climate change in Kazakhstan. *Int. J. Agric. Sci. Food Technol.* **2020**, *6*, 46–49. [CrossRef]
3. Consept for Transition of the Republic of Kazakhstan to Green Economy. 12 September 2013. Available online: https://www.osce.org/files/f/documents/7/e/104851.pdf (accessed on 20 March 2022).
4. Karatayev, M.; Clarke, M. Current Energy Resources in Kazakhstan and the Future Potential of Renewables: A Review. *Energy Procedia* **2014**, *59*, 97–104. [CrossRef]
5. Stigka, E.K.; Paravantis, J.A.; Mihalakakou, G.K. Social acceptance of renewable energy sources: A review of contingent valuation applications. *Renew. Sustain. Energy Rev.* **2014**, *32*, 100–106. [CrossRef]
6. Luostarinen, S.; Normak, A.; Edström, M. Overview of Biogas Technology. Baltic MANURE WP6 Energy Potentials. 2011. Available online: https://www.build-a-biogas-plant.com/PDF/baltic_manure_biogas_final_total.pdf (accessed on 20 March 2022).
7. Adeoti, O.; Ilori, M.O.; Oyebisi, T.O.; Adekoya, L.O. Engineering design and economic evaluation of a family-sized biogas project in Nigeria. *Technovation* **2000**, *20*, 103–108. [CrossRef]
8. Rahman, M.M.; Hasan, M.M.; Paatero, J.V.; Lahdelma, R. Hybrid application of biogas and solar resources to fulfill household energy needs: A potentially viable option in rural areas of developing countries. *Renew. Energy* **2014**, *68*, 35–45. [CrossRef]
9. O'Connor, S.; Ehimen, E.; Pillai, S.C.; Black, A.; Tormey, D.; Bartlett, J. Biogas production from small-scale anaerobic digestion plants on European farms. *Renew. Sustain. Energy Rev.* **2021**, *139*, 110580. [CrossRef]
10. Matsui, K. Wood Resources Management: A Case Study of the Aral Region, Kazakhstan. Ph.D. Thesis, Kyoto University, Kyoto, Japan, 2019. [CrossRef]
11. Kerimray, A.; De Miglio, R.; Rojas-Solórzano, L.; Gallachóir, B.Ó. Household energy consumption and energy poverty in Kazakhstan. In *IAEE Energy Forum*; International Association for Energy Economics: Cleveland, OH, USA, 2007.
12. Dziuba, K.; Todorow, M.; Kowalik, A.; Góra, R.; Bojanowicz-Bablok, A.; Kijenska, L.M.; Tokarz, A.; Baranski, B.; Gworek, G. Carbon footprint in fertilizer production as a tool for reduction of GHG emissions. In Proceedings of the 22nd SETAC Europe LCA Case Study Symposium, Montpellier, France, 20–22 September 2016.
13. Wood, S.; Cowie, A. *A Review of Greenhouse Gas Emission Factors for Fertiliser Production*; The Climate Technology Centre and Network (CTCN): Copenhagen, Denmark, 2004.

14. Liang, Y.; Zhen, L.; Zhang, C.; Hu, Y. Consumption of products of livestock resources in Kazakhstan: Characteristics and influencing factors. *Environ. Dev.* **2020**, *34*, 100492. [CrossRef]
15. Tazhibaev, S.; Musabekov, K.; Yesbolova, A.; Ibraimova, S.; Mergenbayeva, A.; Sabdenova, Z.; Seidahmetov, M. Issues in the Development of the Livestock Sector in Kazakhstan. *Procedia Soc. Behav. Sci.* **2014**, *143*, 610–614. [CrossRef]
16. Xu, S.; He, L.; Ning, J.; Wang, X.; Jing, C.; Ao, W.; Hu, Q. *BRI and International Cooperation in Industrial Capacity*; Taylor & Francis: London, UK, 2020; pp. 57–87.
17. Islyami, A.; Aldashev, A.; Thomas, T.S.; Dunston, S. Impact of Climate Change on Agriculture in Kazakhstan. *Silk Road A J. Eurasian Dev.* **2020**, *2*, 66–88. [CrossRef]
18. Biogas Plants in Kazakhstan. 2021. Available online: https://inbusiness.kz/ru/post/gde-eshe-v-kazahstane-rabotayut-biogazovye-ustanovki (accessed on 20 March 2022).
19. Ministry of National Economy of the Republic of Kazakhstan (Ed.) *Regions of Kazakhstan*; Ministry of National Economy of the Republic of Kazakhstan: Nur-Sultan, Kazakhstan, 2021.
20. Rocha-Meneses, L.; Zannerni, R.; Inayat, A.; Abdallah, M.; Shanableh, A.; Ghenai, C.; Kamil, M.; Kikas, T. Current progress in anaerobic digestion reactors and parameters optimization. *Biomass Convers. Biorefinery* **2022**, 1–24. [CrossRef]
21. Rocha-Meneses, L.; Otor, O.F.; Bonturi, N.; Orupold, K.; Kikas, T. Bioenergy Yields from Sequential Bioethanol and Biomethane Production: An Optimized Process Flow. *Sustainability* **2019**, *12*, 272. [CrossRef]
22. Najafi, B.; Ardabili, S.; Band, S. Spent mushroom compost (SMC) as a source for biogas production in Iran. *Eng. Appl. Comput. Fluid Mech.* **2019**, *13*, 967–982. [CrossRef]
23. Nie, E.; He, P.; Zhang, H.; Hao, L.; Shao, L.; Lü, F. How does temperature regulate anaerobic digestion? *Renew. Sustain. Energy Rev.* **2021**, *150*, 111453. [CrossRef]
24. Manyapu, V.; Kumar, A.; Kumar, R. Psychrophilic biomethanation for enhanced bioenergy production in cold regions. *Clean Technol. Environ. Policy* **2021**, 1–16. [CrossRef]
25. Garfí, M.; Ferrer-Martí, L.; Villegas, V.; Ferrer, I. Psychrophilic anaerobic digestion of guinea pig manure in low-cost tubular digesters at high altitude. *Bioresour. Technol.* **2011**, *102*, 6356–6359. [CrossRef] [PubMed]
26. Fjørtoft, K.; Morken, J.; Hanssen, J.F.; Briseid, T. Methane production and energy evaluation of a farm scaled biogas plant in cold climate area. *Bioresour. Technol.* **2014**, *169*, 72–79. [CrossRef] [PubMed]
27. Martí-Herrero, J.; Alvarez, R.; Cespedes, R.; Rojas, M.R.; Conde, V.; Aliaga, L.; Balboa, M.; Danov, S. Cow, sheep and llama manure at psychrophilic anaerobic co-digestion with low cost tubular digesters in cold climate and high altitude. *Bioresour. Technol.* **2015**, *181*, 238–246. [CrossRef]
28. Perrigault, T.; Weatherford, V.; Martí-Herrero, J.; Poggio, D. Towards thermal design optimization of tubular digesters in cold climates: A heat transfer model. *Bioresour. Technol.* **2012**, *124*, 259–268. [CrossRef]
29. Aoki, K.; Umetsu, K.; Nishizaki, K.; Takahashi, J.; Kishimoto, T.; Tani, M.; Hamamoto, O.; Misaki, T. Thermophilic biogas plant for dairy manure treatment as combined power and heat system in cold regions. *Int. Congr. Ser.* **2006**, *1293*, 238–241. [CrossRef]
30. Curry, N.; Pillay, P. Integrating solar energy into an urban small-scale anaerobic digester for improved performance. *Renew. Energy* **2015**, *83*, 280–293. [CrossRef]
31. Martí-Herrero, J. *Biodigestores Familiares: Guía de Diseño y Manual de Instalación (2008)*; Cooperación Técnica Alemana-GTZ: La Paz, Bolivia, 2015.
32. Smith, A.; Skerlos, S.; Raskin, L. Anaerobic membrane bioreactor treatment of domestic wastewater at psychrophilic temperatures ranging from 15 °C to 3 °C. *Environ. Sci. Water Res. Technol.* **2014**, *1*, 56–64. [CrossRef]
33. Guo, H.; Yu, Z.; Thompson, I.P.; Zhang, H. A contribution of hydrogenotrophic methanogenesis to the biogenic coal bed methane reserves of Southern Qinshui Basin, China. *Appl. Microbiol. Biotechnol.* **2014**, *98*, 9083–9093. [CrossRef] [PubMed]
34. Saady, N.M.C.; Massé, D.I. Impact of organic loading rate on the performance of psychrophilic dry anaerobic digestion of dairy manure and wheat straw: Long-term operation. *Bioresour. Technol.* **2015**, *182*, 50–57. [CrossRef] [PubMed]
35. Wei, S.; Zhang, H.; Cai, X.; Xu, J.; Fang, J.; Liu, H. Psychrophilic anaerobic co-digestion of highland barley straw with two animal manures at high altitude for enhancing biogas production. *Energy Convers. Manag.* **2014**, *88*, 40–48. [CrossRef]
36. Jang, H.M.; Choi, Y.-K.; Kan, E. Effects of dairy manure-derived biochar on psychrophilic, mesophilic and thermophilic anaerobic digestions of dairy manure. *Bioresour. Technol.* **2018**, *250*, 927–931. [CrossRef] [PubMed]
37. Zhang, Y.; Guo, B.; Zhang, L.; Zhang, H.; Liu, Y. Microbial community dynamics in granular activated carbon enhanced up-flow anaerobic sludge blanket (UASB) treating municipal sewage under sulfate reducing and psychrophilic conditions. *Chem. Eng. J.* **2021**, *405*, 126957. [CrossRef]
38. Demartini, E.; Gaviglio, A.; Gelati, M.; Cavicchioli, D. The Effect of Biogas Production on Farmland Rental Prices: Empirical Evidences from Northern Italy. *Energies* **2016**, *9*, 965. [CrossRef]
39. Manesh, K.M.H.; Rezazadeh, A.; Kabiri, S. A feasibility study on the potential, economic, and environmental advantages of biogas production from poultry manure in Iran. *Renew. Energy* **2020**, *159*, 87–106. [CrossRef]
40. Shibata, M.; Terada, F. Factors affecting methane production and mitigation in ruminants. *Anim. Sci. J.* **2010**, *81*, 2–10. [CrossRef]
41. Noorollahi, Y.; Kheirrouz, M.; Asl, H.F.; Yousefi, H.; Hajinezhad, A. Biogas production potential from livestock manure in Iran. *Renew. Sustain. Energy Rev.* **2015**, *50*, 748–754. [CrossRef]
42. Eriksson, O.; Hadin, Å.; Hennessy, J.; Jonsson, D. Life Cycle Assessment of Horse Manure Treatment. *Energies* **2016**, *9*, 1011. [CrossRef]

43. Durán Aranguren, D.; Torres, M.A.C.; Sierra, R.; Gordillo, A.R.; Gordillo, G.; Rodríguez, M.O. Analysis of the Potential Biogas Production from Pig Manure in Pig Farms Located in Colombia. In Proceedings of the 29th European Biosmass Conference & Exhibition, online, 26–29 April 2021.
44. Khan, M.U.; Ahmad, M.; Sultan, M.; Sohoo, I.; Ghimire, P.C.; Zahid, A.; Sarwar, A.; Farooq, M.; Sajjad, U.; Abdeshahian, P.; et al. Biogas Production Potential from Livestock Manure in Pakistan. *Sustainability* **2021**, *13*, 6751. [CrossRef]
45. Bendová, H.; Friess, K.; Bara, J.E.; Izák, P. Single-step purification of raw biogas to biomethane quality by hollow fiber membranes without any pretreatment—An innovation in biogas upgrading. *Sep. Purif. Technol.* **2018**, *203*, 36–40.
46. Jain, M.; Singh, R.; Tauro, P. Anaerobic digestion of cattle and sheep wastes. *Agric. Wastes* **1981**, *3*, 65–73. [CrossRef]
47. Lemmer, A.; Oechsner, H.; Jungbluth, T. Investigation of the methane potential of horse manure. *Agric. Eng. Int. CIGR J.* **2013**, *15*, 161–172.
48. Zhang, D.; Lin, C.; Zhang, Y.; Zhao, L.; Liu, H.; Liu, Z. Effect of organic loading rate on anaerobic digestion of pig manure: Methane production, mass flow, reactor scale and heating scenarios. *J. Environ. Manag.* **2018**, *231*, 646–652.
49. Bedier, E.; Hasham, A. Practical Approach to Improve Biogas Produced from Poultry Manure. *Int. J. Eng. Tech. Res.* **2021**, *9*, 157–160.
50. Norouzi, O.; Heidari, M.; Dutta, A. Technologies for the production of renewable natural gas from organic wastes and their opportunities in existing Canadian pipelines. *Fuel Commun.* **2022**, *11*, 100056. [CrossRef]
51. Vögeli, Y.; Riu Lohri, C.; Gallardo, A.; Diener, S.; Zurbrugg, C. *Anaerobic Digestion of Biowaste in Developing Countries: Practical Information and Case Studies*; Eawag–Swiss Federal Institute of Aquatic Science and Technology: Dübendorf, Switzerland, 2014.
52. *Agriculture, Forestry and Fisheries in the Republic of Kazakhstan*; Agency for Strategic Planning and Reforms of the Republic of Kazakhstan Bureau of National Statistics: Nur-Sultan, Kazakhstan, 2020.
53. Umor, N.A.; Ismail, S.; Abdullah, S.; Huzaifah, M.H.R.; Huzir, N.M.; Mahmood, N.A.N.; Zahrim, A.Y. Zero waste management of spent mushroom compost. *J. Mater. Cycles Waste Manag.* **2021**, *23*, 1726–1736. [CrossRef]
54. Xu, X.; Yuan, X.; Zhang, Q.; Wei, Q.; Liu, X.; Deng, W.; Wang, J.; Yang, W.; Deng, B.; Zhang, L. Biochar derived from spent mushroom substrate reduced N_2O emissions with lower water content but increased CH4 emissions under flooded condition from fertilized soils in Camellia oleifera plantations. *Chemosphere* **2021**, *287*, 132110. [CrossRef]
55. On Approval of the Maximum Allowable Load on the Total Area of Pastures. 15 May 2015. Available online: https://adilet.zan.kz/rus/docs/V1500011064 (accessed on 20 March 2022).
56. Robinson, S.; Milner-Gulland, E.J.; Alimaev, I. Rangeland degradation in Kazakhstan during the Soviet era: Re-examining the evidence. *J. Arid. Environ.* **2003**, *53*, 419–439. [CrossRef]
57. 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. [CrossRef]
58. Robinson, S.; Bozayeva, Z.; Mukhamedova, N.; Djanibekov, N.; Petrick, M. Ranchers or pastoralists? Farm size, specialisation and production strategy amongst cattle farmers in south-eastern Kazakhstan. *Pastoralism* **2021**, *11*, 31. [CrossRef]