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Evaluation of Biogas Potential from Livestock Manures and Multicriteria Site Selection for Centralized Anaerobic Digester Systems: The Case of Jalisco, México

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Abstract: The state of Jalisco is the largest livestock producer in Mexico, leading in the production of swine, eggs, and milk. This immense production generates enormous amounts of waste as a byproduct of the process itself. The poor management of livestock-derived waste can lead to multiple environmental problems like nutrient accumulation in soil, water eutrophication, and air pollution. The aim of this work is to establish a replicable geographic information system (GIS)-based methodology for selecting priority sites in which to implement anaerobic digestion units. These units will use multiple parameters that evaluate environmental risks and viability factors for the units themselves. A weighted overlay analysis was used to identify critical regions and, based on the results, clusters of individual livestock production units (LPUs) across the state were selected. Nitrogen and phosphorus recovery, as well as the energetic potential of the selected clusters, were calculated. Four clusters located mainly in the Los Altos region of Jalisco were selected as critical and analyzed. The results indicate that Jalisco has the potential to generate 5.5% of its total electricity demand if the entirety of its livestock waste is treated and utilized in centralized anaerobic digestion units. Additionally, 49.2 and 31.2 Gg of nitrogen and phosphorus respectively could be valorized, and there would be an estimated total reduction of 3012.6 Gg of carbon dioxide equivalent (CO_2eq).

Keywords: GIS-based methodology; livestock manure; anaerobic digestion; energy production; spatial analysis; waste valorization

1. Introduction

1.1. Livestock Waste Management

The poor management of livestock waste contributes to environmental problems. The main environmental concerns regarding livestock manure can be divided into three categories: accumulation of nutrients in soil, water eutrophication, and air pollution caused by greenhouse gases [1]. Nutrient accumulation in soil can lead to uncontrolled amounts of nitrogen and phosphorus, which can harbor a wide variety of microorganisms that can be pathogenic [2]. Moreover, the animal manure and wastewater generated by a livestock producing unit (LPU) have high concentrations of metals (such as copper, zinc, arsenic, and cadmium), mainly due to the mineral components of livestock feed that are excreted in manure and to the corrosion of the metallic elements in animal enclosures [3,4]. The long-term application of untreated manure to soil can lead to leaching and accumulation in groundwater and water bodies. This in turn can cause increased phytotoxicity, reduced soil fertility and productivity, and toxicity of crops and food products grown on the contaminated soil [5,6].

The transfer of excessive amounts of nutrients and effluents (e.g., slurry, feces, and urine) caused by surface runoff and/or leaching in livestock feeding areas significantly contributes to water quality degradation and eutrophication [7]. Air can be polluted by the emission of greenhouse gases (GHGs) such as methane, nitrous oxide, and ammonia, [8] which contribute to global warming. Unmanaged agricultural and livestock waste may have adverse effects on public health [3,9] due to odors, excessive levels of phosphorus and nitrogen on surface and groundwater, and their potential to spread human pathogens [10]. Further, the ingestion of nitrate and phosphate compounds can lead to diseases such as hypertension, gastrointestinal illness, birth defects, and even infant mortality [11,12].

To decrease the environmental impact of livestock manure various processing technologies have been developed. Composting is widely used because of its cost efficiency [13], though it has been argued that when used as the sole management strategy for these wastes it causes other environmental problems due to the resulting emissions and leachates, which negatively impact air, soil, and water quality [14]. However, there are relatively simple practices that can help prevent leaching, such as increasing compost water holding capacity by adding various bulking agents, protecting the compost from rainfall, and impermeabilizing the composting area correctly [14]. Additionally, composting plants may be equipped with leachate recirculators to ensure that the liquid component generated during the degradation process is integrated back into the process matrix, thus increasing nutrient distribution and pH buffering [15]. Unfortunately, most of the composting done by micro and small producers in Jalisco is carried out in low technification conditions [16].

There are other techniques for manure treatment such as anaerobic digestion (AD), biological treatment, incineration, pyrolysis, and gasification [14,17–19], which are not as commonly used because of their costs, time investment required, and/or ineffectiveness [20]. For instance, AD presents numerous advantages such as pollution reduction (when considering GHG emissions and nutrient leachates), production of valuable byproducts such as fertilizers, and the production of renewable energy. However, AD is expensive, time-consuming, requires high land use, and great volumes of biomass (which is usually gathered by collecting waste from multiple sites) [21,22]. Biological treatment by aerobic digestion is the biochemical oxidative stabilization of wastewater sludge. It can reduce GHG emissions, odors, and pathogens; however, it entails higher capital costs for aeration and monitoring, and it does not produce useful byproducts such as methane [23]. Thermal conversion techniques, such as gasification and pyrolysis, have been widely used to convert organic waste into energy. The main drawback of these treatment methods is that they require a partially dried substrate in order to achieve positive energy recovery rates [24]. Since manure and livestock wastewater have a high moisture content, the required drying process could lead to an energy deficit in the thermal conversion process, thus making manure less economically advantageous when compared to other treatment methods, and therefore unsuitable for managing large volumes of waste [24–26].

Usually manure is considered an output product in livestock systems, which leads to the idea that it is simply residual, but manure should be considered a valuable product because of its nutrient and biogas potential [27]. The controlled production of biogas from said manure can reduce greenhouse gas emissions. Methane is the main component of biogas and its conversion efficiency is dependent on the volatile solids present in manure; methane production values range from 0.02 to 0.45 m^3 CH_4 kg volatile solids^{-1} [28]. Furthermore, biogas can substitute fossil energy services in providing heat, power, and transportation fuels [29]. Once manure has been stabilized, the digestate can be used to improve soil quality and productivity, since it is a significant source of nitrogen and phosphorus and increases soil water retention [27]. The resulting digestate has high ammonium nitrogen concentrations compared to raw manure, and can be effectively used by crops [30–32]. Ammonium nitrogen also shows a strong sorption capacity as it binds to soil sorption complexes, making it less prone to leaching but still available for plant absorption [33,34].

1.2. Livestock Waste Importance and Pollution in Jalisco, Mexico

Livestock waste can become valuable when it is managed correctly, but in Mexico manure is currently one of the main sources of air, soil, and water pollution [35–37]. Mexico is the main emitter of greenhouse gases in Latin America and the only one that is among the 15 highest pollutant-generating nations [38]. Of Mexico's total GHG emissions in 2015, 10% originated from livestock production systems [39] Furthermore, poor agricultural practices promote runoff that contaminates surface and groundwater, which is coupled with the fact that the Mexican territory has slopes that make it susceptible to hydric erosion [40].

Jalisco is one of 32 states in Mexico. It is in the center-west region of the country and has an area of 78,588 km^2 [41]. In 2018 Jalisco had a reported population of more than 8.1 million people distributed among urban (87.9%) and rural (12.1%) areas [42]. Jalisco is the state that produces the most food at a national level, and is the number one producer of certain goods, such as swine, eggs, and milk [43]. INEGI (The National Institute of Statistics and Geography) reported 3,348,965 head of beef, 2,766,180 head of swine, and 78,521,604 head of poultry for the state of Jalisco in 2017. These high food production rates also make Jalisco the main generator of agricultural waste, which translates into a serious environmental problem if not managed properly. On the other hand, with the right treatment waste could become an economic advantage because of the fertilizer it could produce, and the thermal and electrical energy potential it offers. According to the Law of Integral Management of Waste in Jalisco (2007), every agricultural company must integrate biodegradable waste into their productive processes, using it as an energy source or compost so it does not damage the environment [44].

Jalisco's hydrological system (Figure 1) has undergone a process of eutrophication, particularly throughout the Lerma-Santiago basin [45,46]. Several researchers agree that more than 80% of the water bodies in Jalisco are severely polluted, although none to the same degree as the Santiago River, which frequently presents anoxic conditions [45,47,48]. Anoxic conditions develop when the consumption of oxygen by biological or chemical processes exceeds the rate of resupply by vertical mixing and diffusion, and in many cases it is associated with the runoff of nitrates from fertilizers [49–51]. Lakes such as Cajititlán, Zapotlán, and Chapala present a high degree of eutrophication as reported in several studies [45,52–55].

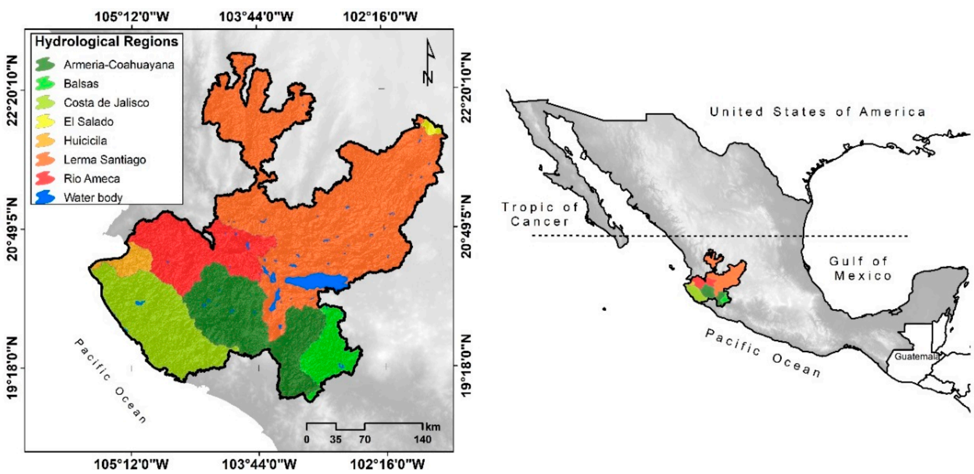

Figure 1. Hydrological regions of the state of Jalisco (within national context).

1.3. Cluster Spatial Analysis for the Anaerobic Treatment of Livestock Waste

In recent years, an increasing awareness that AD can help mitigate odor, assist in nutrient recovery, and offer economic benefits, has stimulated renewed interest in the technology [22,56,57]. Animal waste has the potential to be valorized and because these resources tend to be highly site-specific, it is important to know their location as well as the quantity produced [21,22,58]. Governments and industries around the world have done research into clustered energy schemes of AD [21,22]. Given that geographical data and spatial factors (biomass availability, transportation distances, urbanization of the area, road infrastructure, protected areas, and environmental features) play a central role in identifying optimal locations for siting biogas plants, geographic information systems (GIS) have been used in previous studies [22,56–59]. Some studies have also analyzed the spatial distribution of potential biomass feedstock in order to identify optimal locations for biogas plants [59–62].

For these reasons, it is evident that agricultural waste, specifically animal manure, has greatly contributed to water and air pollution in Jalisco. Nonetheless, improving manure management has the potential to improve the economics of agriculture; this is dependent on spatial targeting of key contributing areas [63,64]. Spatial analysis applied to manure management of farm clusters can have positive impacts on economic and environmental factors, especially for small and medium livestock production farms [65,66]. Cost-effective benefits are presented considering that the expenses of implementation can become a major obstacle if the optimization analysis is not done correctly. On the other hand, cluster management can offer more control over waste pollutants and increase the valorization potential of manure. Framing manure management as a geographical and mathematical optimization problem can help find an appropriate solution that assists in reducing operational costs and maximizing environmental efficiency [65]. The aim of this study is to assess the energetic, nutrient, and environmental potential of livestock waste in Jalisco, considering the implications for the state's hydrological systems. As a contribution to the literature, the methodology proposed here implements a weighted overlay analysis with specific weighted categories that account for both viability factors and environmental parameters, in order to identify viable places to install centralized AD units, as well as the most critical regions for reducing the environmental impact of the Jalisco livestock industry. A system such as the one proposed here could help the state of Jalisco move closer to meeting its energy demands and would offer small and medium livestock producers cheaper and more efficient treatment for their waste, while also greatly reducing greenhouse gas emissions and nutrient pollution of soils and water bodies, which are issues of great importance for the state.

The proposed centralized anaerobic digestion units (CADUs) offer multiple benefits compared to individual farm-based AD units, such as requiring a lower energy consumption and lower individual investment. However, transportation costs greatly influence the operation and viability of CADUs and spatial parameters must be considered in order to reduce transportation costs between CADUs and the substrate providers, and between CADUs and the final consumers of the digestate process [67]. In this study, the distance between the potential sites for CADUs and the nearest LPUs was considered for the weighted overlay analysis, however, further studies should estimate transportation costs considering also the distribution of the digestate from the CADUs to the final consumers as part of the weighted overlay analysis. Other spatial parameters that could help improve the accuracy of the model include the distance to the road infrastructure and electric grid. Proximity to an existing road network and to the existing electrical grid would be, of course, advantageous. A wider range of substrates, such as crop waste, should also be considered (for co-digestion) in future studies.

2. Methods

The complete methodological approach used in this study is summarized on Figure 2.

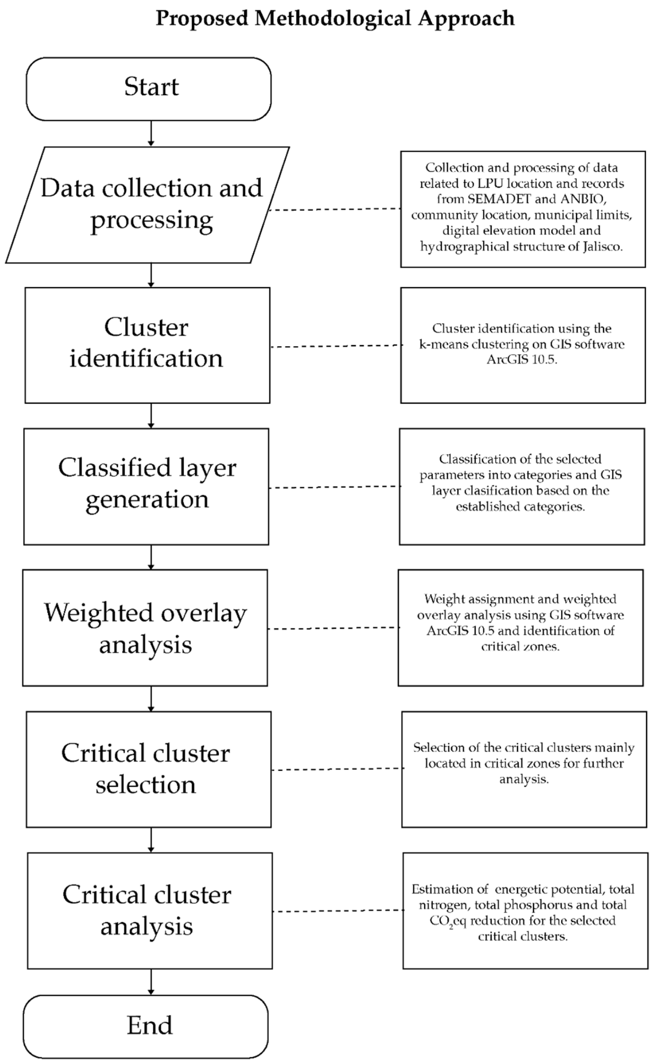

Figure 2. Graphical description of the proposed methodology.

2.1. *Data Collection and Processing*

Data related to the location and headcount of LPUs were obtained from historical records provided by SEMADET (Environment and Land Development Agency) for registered livestock producers updated to January 2019, in conjunction with records obtained from ANBIO (National Biomass Atlas). All LPU locations and headcounts were verified to identify any errors in the dataset by calling the registered numbers for the LPUs. Common errors found in the data were abnormal or incomplete coordinates as well as incomplete or abnormal headcount data. These were all corroborated with livestock producers and updated.

Data used to determine the hydrographic structure of Jalisco, including both superficial water bodies and surface runoffs, were obtained from INEGI and CEA (State Water Commission), available as open access data. As for the data relating to the digital elevation model, location of urban communities, municipal limits, and state limits, they were gathered from the official geographical data provided by INEGI [68].

A geographic information system was used to assess the location of the LPUs in Jalisco as well as the hydrographic structure around them. A GIS is designed to spatially map resources and is valuable for a wide range of public and private companies to plan strategies and manage infrastructure in a region [69–71].

2.2. Identification of Critical Clusters

Using the k-means clustering method in ArcGIS 10.5 software, ten initial clusters were defined in order to group together the different LPUs scattered across the state. The k-means method allocates each point to a specified number of clusters and attempts to minimize the global goodness-of-fit measures by using a sum squared error (SSE). This measure is the distance from each point to the centroid of the cluster [72]. Therefore, in the context of this study, clusters may be defined as spatial groupings of LPUs that are close to each other.

In order to identify the critical clusters and determine the locations for the CADUs we completed a weighted overlay analysis. For this purpose, we generated a weighted index matrix to classify and rank the rasters according to the specific parameters. Five parameters were evaluated in order to locate priority zones for installing CADUs for farm clusters, taking into consideration total waste production and environmental characteristics that favor pollutant transfer and superficial water pollution: (1) total livestock waste produced by the LPU closest to the potential sites; (2) distance between the potential sites and the nearest livestock production unit; (3) distance between the sites and the nearest urban community; (4) distance between the sites and the nearest superficial water body; and (5) slope of the sites. In this case, the parameters to assess the suitability of a given location for a CADU were selected based on previous studies, as shown in Table 1. Several other spatial parameters have been included in similar studies, such as distance to roads, to the electric grid, and to airports, and floodplains, among others [21,22,56–59,73–76].

2.2.1. Total Livestock Waste Produced by the LPU Closest to the Potential Sites

It is important to consider the size of the production unit located closest to the potential sites in order to evaluate and categorize its impact on the surrounding areas, since higher amounts of waste represent a higher risk of pollution. A small production unit, on the other hand, could lead to shortages in the supply of the substrate for the CADU [77,78].

To that end, total waste per species ($\boldsymbol{T_i}$) was calculated for each LPU according to Equation (1), using total headcounts for each species in a specific LPU ($\boldsymbol{H_i}$) and the mean daily waste production associated with poultry, cattle, and swine production ($\boldsymbol{R_i}$), which was estimated using reports from multiple authors (presented in Table 2). The total daily waste production values corresponding to poultry, cattle, and swine production were added to obtain the total daily waste production ($\boldsymbol{T_w}$) for each LPU, as shown in Equation (2).

$$\boldsymbol{T_i} = \boldsymbol{H_i} \times \boldsymbol{R_i} \quad (1)$$

$$\boldsymbol{T_w} = \sum \boldsymbol{T_i} \quad (2)$$

Table 1. Parameters used to assess the suitability of a given location for siting a centralized anaerobic digestion unit (CADU) reported in previous studies. LPU = livestock production unit.

Authors	Year	Total Livestock Waste Production at Nearest LPU to the Site	Distance between the Site and the Nearest LPU	Distance between the Site and the Nearest Urban Community	Distance between the Site and the Nearest Superficial Water Body	Slope of the Site	Study Region
Mukherjee et al. [73]	2015	X	X	X	X		Connecticut, USA
Comber et al. [74]	2015	X	X				East Midlands, UK
Ma et al. [22]	2004	X	X	X	X	X	New York, USA
Venier and Yabar [56]	2017	X	X	X	X		Buenos Aires, Argentina
Zareei [75]	2018	X	X	X	X		Iran
Dagnall, Hill, and Pegg [58]	2000	X	X	X	X		UK
Thompson, Wang, and Li [57]	2013	X	X	X	X	X	Vermont, USA
Höhn et al. [59]	2014	X	X	X			Southern Finland
Batzias, Sidiras, and Spryou [21]	2005	X	X				Greece
Zubaryeva et al. [76]	2012	X	X	X	X	X	Apulia Region, Italy

Table 2. Waste production rates per species.

Livestock Species	Waste Production Rates per Species (R_i)									
	kg head^{-1} day^{-1}			kg head^{-1} month^{-1}			kg head^{-1} year^{-1}			
	Value	**Average**	**Range**	**Value**	**Average**	**Range**	**Value**	**Average**	**Range**	**Source**
Cattle	31.6	35.37	30.74–47.70	960.96	1075.73	934.80–1450.55	11,534.00	12,911.26	11,220.10–17,410.5	[79]
	36.98			1124.56			13,497.70			[80]
	30.74			934.80			11,220.10			[81]
	32.50			988.33			11,862.50			[82]
	47.70			1450.56			17,410.50			[83]
	32.72			995.02			11,942.80			[84]
Swine	5.72	8.03	4.80–15.15	173.95	244.39	145.96–460.71	2087.80	2933.38	1752.00–5529.75	[85]
	11.47			348.80			4186.55			[79]
	4.80			145.97			1752.00			[80]
	15.15			460.71			5529.75			[82]
	6.03			183.37			2200.95			[84]
	5.05			153.57			1843.25			[86]
Poultry	0.35	0.19	0.09–0.35	10.64	5.73	2.73–10.64	127.75	68.74	32.85–127.75	[85]
	0.10			3.04			36.50			[79]
	0.25			7.60			91.25			[80]
	0.17			5.17			62.05			[82]
	0.17			5.17			62.05			[84]
	0.09			2.74			32.85			[86]

2.2.2. Distance between the Potential Sites and the Nearest Livestock Production Unit

Just like the total waste produced, the distance between the site and the nearest LPU also affects the feasibility of the project, given that long distances between the sites will translate into higher transportation costs for collecting the substrates for the CADU. Additionally, locations closer to an LPU suffer from higher levels of pollution since most producers dispose of their waste near the site where it is generated [75,87].

2.2.3. Distance between the Potential Sites and the Nearest Urban Community

LPUs located in the vicinities of urban communities can affect their surroundings and therefore have a negative effect on the communities within their range. CADUs operating correctly have a lower impact on the surrounding communities compared to places with poor management practices, therefore they can be located closer to populated areas without affecting their inhabitants [88,89].

2.2.4. Distance between the Potential Sites and the Nearest Superficial Water Body

Generally, LPUs treat and dispose of their waste mainly by field application [90,91] and, as previously mentioned, this causes multiple environmental issues. It is important to focus on sites closer to superficial water bodies as waste deposited closer to runoffs, rivers, or lakes has a more direct impact on the water quality of the whole basin. CADUs should not have leaks or infiltration as this would decrease the commercially valuable byproducts that can otherwise be obtained. Furthermore, it would represent a risk of surface water contamination [92,93].

2.2.5. Slope of Potential Sites

Steeper terrains will have higher levels of runoff compared to flatter terrains, which make them more prone to causing higher environmental impacts through leakage or infiltration, since they can reach superficial water bodies more quickly [88,93].

For each parameter, a raster was obtained. A raster is defined as a densely packed array of pixels, each with a specific value or intensity assigned to it [94]. Thiessen polygons were generated based on the total waste production calculated for the corresponding farms. These polygons were later transformed into raster format. The distances between the potential sites and the nearest livestock production unit, the potential sites and the nearest urban community, and the potential sites and the nearest superficial water body were all transformed into raster format images by calculating the Euclidean distance for each variable. The slope of the potential sites was calculated based on the digital elevation model of the area and then converted into a raster format [95].

For the weighted index table (Table 3), each parameter was modeled and assigned suitability values ranging from 1 to 5. The raster images were classified based on a 1–5 scale depending on how these parameters increase the risk of pollution of the areas where they are located and the viability of the implementation of CADUs; 1 represents the lowest risk and viability and 5, the highest. The weight of each parameter was assigned based on reported studies [96–98] and experienced specialists who were consulted for this particular exercise.

The weighted overlay analysis using the obtained raster images was done according to Equation (3), where R is the resulting risk factor for each pixel in the resulting raster, $\boldsymbol{Wi}$ is the assigned weight for each variable, and $\boldsymbol{Vi}$ is the value of the corresponding reclassified raster for each pixel.

$$\sum_{i=1}^{5}[(\boldsymbol{Wi}*\boldsymbol{Vi})] \quad (3)$$

As a result, a classification raster was obtained where each pixel is classified on a scale from 1 to 5 corresponding to the risk of environmental pollution resulting from management of livestock waste and the viability of the implementation of CADUs based on the previously mentioned parameters. The zones with scores of 5 were selected as critical zones, since they present the highest viability and environmental risk factors.

Based on the weighted overlay analysis and the critical zones identified by it, the critical percentage of each cluster was determined by calculating the percentage of LPU sites located in critical zones for each of the previously proposed clusters. Clusters with 75% or more of their LPUs located in critical zones were selected as critical clusters.

Table 3. Weighted index table.

Parameter	Unit	Weight (%)	Value				
			1	2	3	4	5
Total livestock waste production at nearest LPU to the site	Ton day^{-1}	30	0–1	1–5	5–10	10–20	>20
Distance between the site and the nearest LPU	m	30	>2000	1500–2000	1000–1500	500–1000	0–500
Distance between the site and the nearest urban community	m	10	>2000	1500–2000	1000–1500	500–1000	0–500
Distance between the site and the nearest superficial water body	m	20	>500	300–500	100–300	50–100	0–50
Slope of the site	%	10	0–2	2–4	4–6	8–10	>10

2.3. Critical Cluster Analysis

In order to evaluate the viability of implementing CADUs, the following parameters were selected: total waste production; total nitrogen and phosphorus digestate recovery; methane production potential; electric energy potential; and carbon dioxide equivalent (CO_2eq) reduction. These were all calculated for the selected critical clusters and the municipalities that form them using bibliographical considerations (Table 4). Calculations regarding waste generation per species, volatile solid fraction in waste, and methane generation potential were done using the mean, minimum, and maximum values reported in literature (Tables 2 and 4) in order to obtain the minimum, maximum, and average estimates (Tables 6 and 7). The same values were calculated at a state level by adding together the values found for all LPUs in the state inventory.

Table 4. Volatile solid fraction and methane production rates per species.

	Volatile Solid Fraction (Vs) (%)				Methane Production (Mp) (Nm^3 CH_4 kg Volatile Solids^{-1})			
Livestock Species	**Value**	**Average**	**Range**	**Source**	**Value**	**Average**	**Range**	**Source**
Cattle	10.79 16	16.80	10.79–28.8	[99] [100]	0.24	0.19	0.13–0.24	[28]
	28.8 10.86			[101] [84]	0.13			[28]
	13.12 21.7			[102] [104]	0.21			[103]
Swine	12.23 20	14.80	6.22–22	[99] [100]	0.29	0.34	0.29–0.45	[28]
	22 8.59			[101] [84]	0.45			[28]
	20.02 6.22			[102] [28]	0.29			[103]
Poultry	19.38 17	24.80	17–37.21	[99] [100]	0.157	0.19	0.02–0.39	[28]
	19.5 19.11			[101] [84]	0.023			[28]
	37.21 36.7			[102] [106]	0.39			[105]

2.3.1. Nitrogen and Phosphorus Recovery

Using the waste production for each species for each individual LPU (which was previously calculated), total nitrogen recovery per LPU (N_T) was found using Equation (4), where Nc represents the nitrogen composition of each species' waste and N_T represents the total nitrogen recovery from an individual LPU. For this study the Nc values used were 23.3, 30.8, and 51.0 g of nitrogen per kg of waste for cattle, swine, and poultry respectively, as reported by Kirchmann and Witter [107].

$$N_T = \sum Nc_i \times T_i \quad (4)$$

Total phosphorus recovery per individual LPU (P_T) was calculated using Equation (5), where P_T represents the total phosphorus recovery per LPU and Pc indicates the weight fraction of the phosphorus present in each species' waste. For this study the Pc values used were 8.0, 29.1, and 21.1 g of phosphorus per kg of waste for cattle, swine, and poultry respectively, as reported by Barnett [108].

$$P_T = \sum Pc_i \times T_i \quad (5)$$

Total nitrogen and total phosphorus recovery values for the selected critical clusters and their corresponding municipalities were calculated by adding the total nitrogen and phosphorus recovery values for each of the LPUs belonging to the cluster or municipality.

2.3.2. Energetic Potential Calculation

The percentage of volatile solids present in livestock waste (Vs) and the methane production from volatile solids (Mp) were obtained (Table 4).

The total methane production (M_T) (reported in normal cubic meters, Nm^3) for each LPU was calculated based on the total volatile solid content in the waste produced by each species and the methane production rates presented in Table 4, given that each species' waste has a different composition and therefore a different methane potential depending on the total volatile solids present in it. The electrical energy potential for each LPU and for each CADU was calculated for two scenarios, as presented in Table 5: (1) using its energetic potential and the most common conversion efficiency (η_A) for small generators [109], where the total electrical potential is represented as Ee_A; and (2) using its energetic potential and the most common conversion efficiency (η_B) for large generators [109], where the total electrical potential is represented as Ee_B. For both scenarios, the total electrical potential was calculated using the energetic capacity (E_m) of methane proposed by Cuellar [110].

$$M_T = \sum Vs_i \times T_i \times Mp_i \quad (6)$$

$$Ee_A = \eta_A \times M_T \times E_m \quad (7)$$

$$Ee_B = \eta_B \times M_T \times E_m \quad (8)$$

The total methane potential and electric energy potential for the selected critical clusters and their corresponding municipalities were determined under the two proposed scenarios by adding together the values that were calculated for their corresponding LPUs.

2.3.3. Greenhouse Gas Emission Calculation and Potential Reduction

Greenhouse gas emissions for each individual LPU and CADU were calculated according to two scenarios, as shown in Table 5:

(1) Calculating the amount of equivalent CO_2 generated by the previously determined amount of waste generated for each LPU if the waste is disposed of directly by field application—as this is the most common practice in Jalisco [90,91]—represented as C_A in Equation (9). N_{N2O} represents the fraction of the total nitrogen present in waste that is transformed into N_2O in field application

conditions. The CO_2 equivalent conversion factors for methane and nitrous oxide used are the ones proposed by the IPCC (Intergovernmental Panel on Climate Change) [111].

$$C_A = (M_T \times 25 \times 67) + (N_T \times N_{N2O} \times 298) \quad (9)$$

(2) The second scenario was calculated for a situation in which the waste generated by each specific LPU is treated by anaerobic digestion in a CADU and the biogas obtained through this process is used for the production of electric energy. This is shown in Equation (10), where C_B represents the total equivalent CO_2 for this scenario and C_m represents the equivalent CO_2 emitted by the combustion of methane during energy generation. Under anaerobic conditions, N_2O generation is substantially reduced and can be considered negligible [112–114].

$$C_B = M_T \times C_m \quad (10)$$

Table 5. Proposed scenarios for greenhouse gas emission calculations.

Scenario	Energetic Potential Calculation	Greenhouse Gas Emission Calculation
A	The methane produced by the anaerobic digestion (AD) process is transformed into electric energy by low efficiency small farm-scale generators (η_A = 25%) [109]	Waste generated by the individual LPUs is disposed of directly by field application, which is the most common practice in Jalisco. N_2O is reportedly generated at a rate of 0.2 kg of N_2O per kg of the nitrogen content of the waste. The CH_4 generated by the uncontrolled degradation of organic matter in soil is also considered. N_2O and CH_4 present values of 298 and 25 kg CO_{2eq} per kg, respectively [111,115].
B	The methane produced by the AD process is transformed into electric energy by high efficiency centralized generators (η_B = 40%) [109].	Waste generated by each specific LPU is treated by anaerobic digestion in a CADU and the biogas obtained through this process is used for the production of electric energy. Since N_2O generation can be negligible during controlled AD only CH_4 generated during the AD process is taken into account. Additionally, as it is used for energy generation, the CH_4 is transformed into CO_2 by combustion at a rate of 2.75 kg of CO_2 per kg of CH_4 [111,115].

The equivalent CO_2 reduction (C_R) was estimated using Equation (11) to evaluate the difference in the total CO_2 equivalent generation between the two proposed scenarios.

$$C_R = C_A - C_B \quad (11)$$

Total CO_2 equivalent generation for both scenarios and total CO_2 reductions for the selected critical clusters and their corresponding municipalities were determined by adding the values calculated for the LPUs belonging to these clusters and municipalities.

The hypotheses explaining the differences between the A and B scenarios regarding electricity potential and CO_2 equivalent generation are summarized in Table 5.

3. Results

Five classificatory maps were created (Figure 3), one for each of the parameters evaluated with its respective classificatory scale. As a result of the weighted overlay analysis, a general map (Figure 4) was made, which indicates the critical zones within each of the initial clusters. These critical zones were highlighted in red as they were assigned the highest possible grade based on the five parameters that were evaluated, which consider environmental risks, CADU viability parameters, and the weights used (shown in Table 3). The total critical area (in red) determined was 5417.10 km^2, which amounts to 6.8% of the total territory of the state.

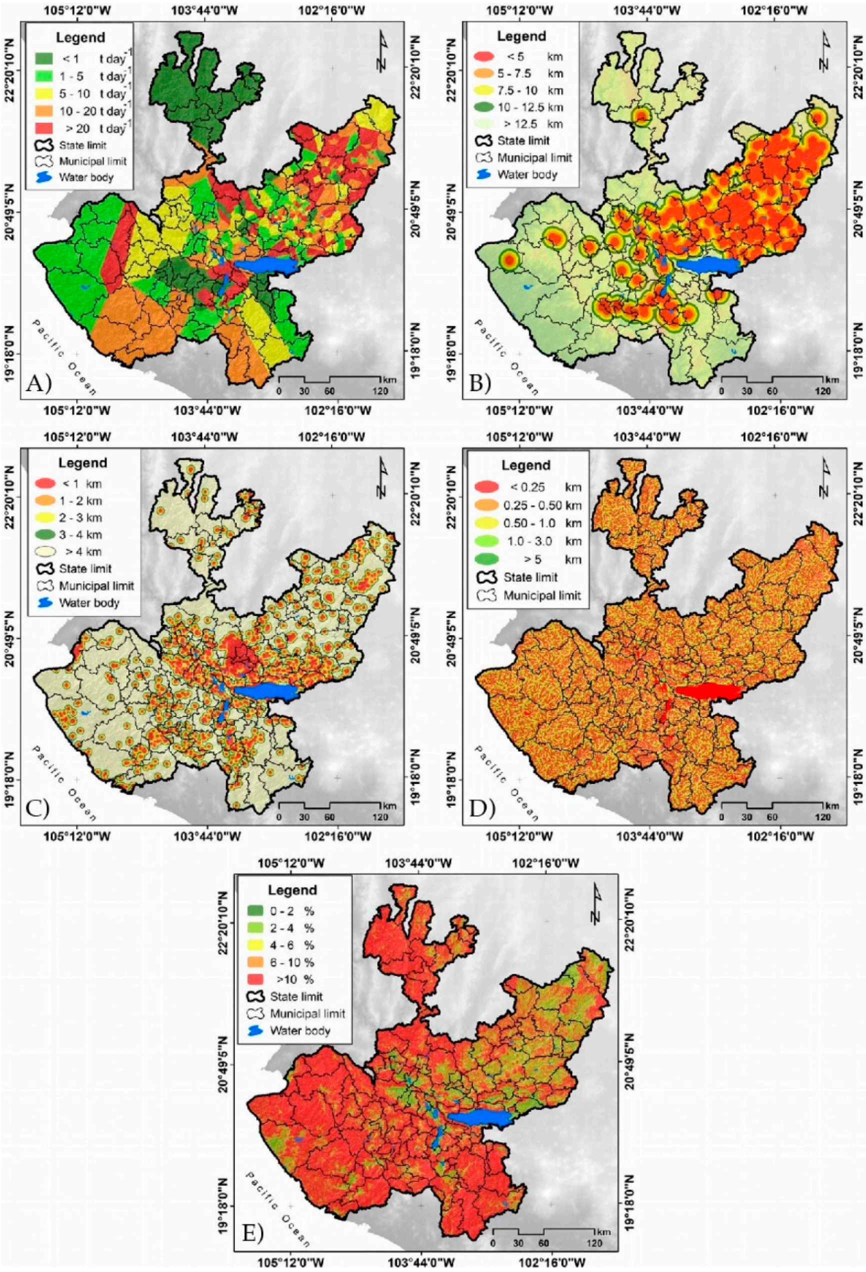

Figure 3. Classification of raster images for: (**A**) Total livestock waste production from the LPU closest to the potential sites. (**B**) Distance from the potential sites to the nearest livestock production unit. (**C**) Distance from the potential sites to the nearest urban community. (**D**) Distance from the potential sites to the nearest superficial water body. (**E**) Site slope.

The percentage of LPUs located within the critical zone (or cluster) was determined for each cluster. The clusters that were found to have 75% or more of their LPUs located within critical zones were classified as critical clusters. Four clusters located in "Los Altos Norte" and "Los Altos Sur" regions had 75% of their LPUs within critical zones. They were therefore identified as critical clusters, and labeled A, B, C, and D as shown in Figure 5.

Tables 6–8 show total values for waste generation, nitrogen and phosphorus recovery, methane production potential, electric energy potential under the two proposed scenarios, and equivalent

CO_2 reduction for the selected critical clusters (where CADUs should be implemented) and the municipalities that they make up (again, considering the two proposed scenarios). The table also shows the total values at a state level. These values are not presented at the LPU level because the focus of this work is on the viability of CADUs to collect wastes within the clusters.

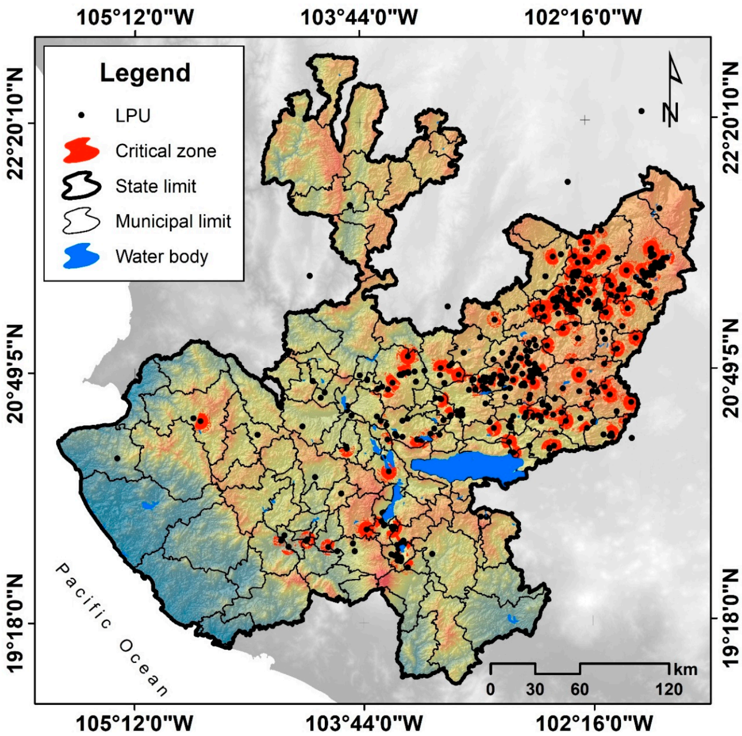

Figure 4. Critical zones identified in Jalisco as a result of the weighted overlay analysis.

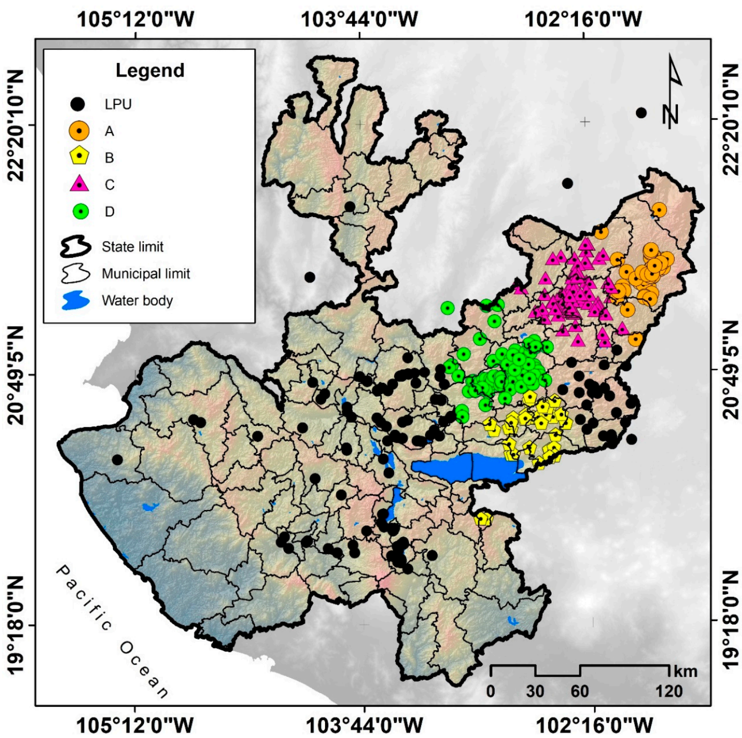

Figure 5. Location of critical clusters within Jalisco.

Table 6. Values calculated for critical clusters A and B.

Cluster	Municipality		Livestock Waste (Gg year^{-1})	Total Nitrogen Recovery (Mg year^{-1})	Total Phosphorus Recovery (Mg year^{-1})	CH_4 (Mg year^{-1})	Electricity Potential A (MW)	Electricity Potential B (MW)	CO_2eq A (Gg year^{-1})	CO_2eq B (Gg year^{-1})	Emission Reduction CO_2eq (Gg year^{-1})
A	Lagos de Moreno	Min	343.08	3930.44	2722.87	3398.79	0.97	1.55	108.39	9.35	99.05
		Mean	594.53	7314.80	4865.64	19,266.00	8.21	13.13	512.29	52.98	459.31
		Max	1099.95	13,571.19	9085.67	76,328.91	21.78	34.85	1989.11	209.91	1779.20
	Unión de San Antonio	Min	22.36	152.06	127.21	250.62	0.07	0.11	7.17	0.69	6.48
		Mean	33.53	240.27	208.07	1039.09	0.44	0.71	26.73	2.86	23.88
		Max	58.58	436.04	386.44	3373.17	0.96	1.54	86.93	9.28	77.65
	Total A	**Min**	**365.45**	**4082.50**	**2850.08**	**3649.41**	**1.04**	**1.67**	**115.57**	**10.04**	**105.53**
		Mean	**628.05**	**7555.07**	**5073.72**	**20,305.09**	**8.65**	**13.84**	**539.03**	**55.84**	**483.19**
		Max	**1158.54**	**14,007.23**	**9472.11**	**79,702.08**	**22.75**	**36.39**	**2076.04**	**219.18**	**1856.85**
B	Atotonilco el Alto	Min	29.83	226.62	203.23	347.59	0.10	0.16	10.04	0.96	9.08
		Mean	47.36	369.96	337.03	1547.4	0.66	1.05	39.88	4.26	35.63
		Max	86.23	686.25	631.50	5097.45	1.45	2.33	131.53	14.02	122.44
	La Barca	Min	32.36	271.18	256.20	391.20	0.11	0.18	11.40	1.08	10.32
		Mean	54.2	454.03	428.97	1850.5	0.79	1.26	47.76	5.09	42.67
		Max	102.16	855.90	808.66	6166.73	1.76	2.82	159.27	16.96	148.95
	Ocotlán	Min	57.86	344.46	260.06	621.18	0.18	0.28	17.58	1.70	15.87
		Mean	81.31	519.81	415.88	2356.38	1	1.61	60.48	6.48	54
		Max	134.93	912.77	760.93	7496.59	2.14	3.42	192.85	20.62	176.98
	Tototlán	Min	184.96	721.85	296.16	1774.70	0.50	0.81	48.67	4.88	43.79
		Mean	218.18	872.71	380.54	4960.16	2.11	3.38	126.02	13.64	112.38
		Max	302.39	1249.00	581.33	14,428.91	4.12	6.59	368.17	39.68	324.38
	Zapotlán del Rey	Min	11.37	95.23	89.97	137.37	0.04	0.06–0.99	4.00–55.93	0.38–5.96	3.62–52.30
		Mean	19.03	159.44	150.64	649.81	0.28	0.44	16.77	1.79	14.98
		Max	35.88	300.55	283.97	2165.48	0.62	0.99	55.93	5.96	52.30
	Total B	**Min**	**316.39**	**1659.32**	**1105.63**	**3272.04**	**0.93**	**1.49**	**91.69**	**9.00**	**82.69**
		Mean	**420.08**	**2375.94**	**1713.05**	**11,364.25**	**4.84**	**7.75**	**290.91**	**31.25**	**259.66**
		Max	**661.60**	**4004.47**	**3066.39**	**35,355.16**	**10.09**	**16.14**	**907.75**	**97.23**	**825.05**

Values presented in bold represent the sum of the values reported for each individual municipality in the corresponding cluster.

Table 7. Values calculated for critical clusters C and D.

Cluster	Municipality		Livestock Waste (Gg year^{-1})	Total Nitrogen Recovery (Mg year^{-1})	Total Phosphorus Recovery (Mg year^{-1})	CH_4 (Mg year^{-1})	Electricity Potential A (MW)	Electricity Potential B (MW)	CO_2eq A (Gg year^{-1})	CO_2eq B (Gg year^{-1})	Emission Reduction CO_2eq (Gg year^{-1})
C	Encarnación de Díaz	Min	206.60	2435.94	1538.43	1906.13	0.54	0.87	62.17	5.24	56.93
		Mean	352.66	4589.53	2791.53	11,063.63	4.71	7.54	296.45	30.42	266.02
		Max	640.03	8456.62	5186.68	45,612.32	13.02	20.83	1190.71	125.43	1133.78
	San Juan de Los Lagos	Min	580.95	7964.80	4898.05	5078.97	1.45	2.32	174.44	13.97	160.48
		Mean	1049.83	15,431.17	9070.54	33,601.92	14.31	22.9	909.04	92.41	816.63
		Max	1947.94	28,585.88	16,893.80	145,769.25	41.60	66.56	3814.60	400.87	3654.13
	Teocaltiche	Min	7.10	138.41	66.87	39.02	0.01	0.02	1.80	0.10	1.70
		Mean	14.05	284.53	133.79	431.13	0.18	0.29	12.17	1.19	10.98
		Max	26.02	525.02	247.52	2278.55	0.65	1.04	60.09	6.27	58.40
	Jalostotitlán	Min	149.33	2515.21	1353.20	1056.25	0.30	0.48	41.40	2.90	38.49
		Mean	284.71	5056.35	2615.32	8943.86	3.81	6.1	247.48	24.6	222.88
		Max	529.26	9350.14	4855.01	43,283.50	12.35	19.76	1137.81	119.03	1099.32
	Total C	**Min**	**943.97**	**13,054.37**	**7856.55**	**8080.37**	**2.30**	**3.69**	**279.81**	**22.22**	**257.59**
		Mean	**1701.26**	**25,361.58**	**14,611.18**	**54,040.53**	**23.02**	**36.83**	**1465.13**	**148.61**	**1316.52**
		Max	**3143.25**	**46,917.67**	**27,183.01**	**236,943.62**	**67.62**	**108.19**	**6203.22**	**651.59**	**5945.63**
D	Acatic	Min	54.51	492.62	436.33	637.50	0.18	0.29	18.87	1.75	17.12
		Mean	92.25	848.83	740.5	3127.88	1.33	2.13	81.2	8.6	72.6
		Max	173.70	1594.98	1393.79	10,806.85	3.08	4.93	279.68	29.72	262.56
	Tepatitlán de Morelos	Min	201.33	9024.47	1686.64	1872.81	0.53	0.86	62.25	5.15	57.10
		Mean	359.93	4943.44	3076.59	11,652.53	4.96	7.94	312.87	32.04	280.82
		Max	670.07	9175.12	5740.97	48,635.18	13.88	22.21	1270.56	133.75	1213.46
	Zapotlanejo	Min	32.78	306.42	167.07	290.22	0.08	0.13	9.08	0.80	8.28
		Mean	49.66	554.22	298.94	1394.39	0.59	0.95	37.22	3.83	33.39
		Max	82.61	993.04	544.69	5601.77	1.60	2.56	145.96	15.40	137.68
	Total D	**Min**	**288.61**	**3387.79**	**2290.05**	**2800.53**	**0.80**	**1.29**	**90.20**	**7.70**	**82.50**
		Mean	**501.85**	**6346.49**	**4116.03**	**16,174.8**	**6.89**	**11.02**	**431.29**	**44.48**	**386.81**
		Max	**926.38**	**11,763.14**	**7679.45**	**65,043.82**	**18.56**	**29.70**	**1696.20**	**178.87**	**16,13.70**

Values presented in bold represent the sum of the values reported for each individual municipality in the corresponding cluste.

Table 8. Values calculated for critical clusters (total).

		Livestock Waste (Gg year^{-1})	Total Nitrogen Recovery (Mg year^{-1})	Total Phosphorus Recovery (Mg year^{-1})	CH_4 (Mg year^{-1})	Electricity Potential A (MW)	Electricity Potential B (MW)	CO_2eq A (Gg year^{-1})	CO_2eq B (Gg year^{-1})	Emission Reduction CO_2eq (Gg year^{-1})
Sum Critical Clusters	Min	1914.42	22,183.98	14,102.31	17,802.36	5.08	8.13	577.28	48.96	528.32
	Mean	3251.23	41,639.08	25,513.98	101,884.68	43.4	69.44	2726.36	280.18	2446.18
	Max	5889.77	76,692.50	47,400.96	417,044.68	119.02	190.43	10,883.20	1146.87	10,354.89
Jalisco	Min	2370.47	26,482.52	17,365.25	22,660.38	6.47	10.35	724.34	62.32.33	662.03
	Mean	4002.62	49,240.41	31,153.68	126,025.78	53.63	85.88	3354.19	346.57	3012.62
	Max	7256.18	90,752.42	57,931.67	505,210.76	144.18	230.69	13,171.15	1389.33	12,509.12

Nc values used were 23.3, 30.8, and 51.0 g of nitrogen per kg of waste for cattle, swine, and poultry respectively, as reported by Kirchmann and Witter [107]. ***Pc*** values used were 8.0, 29.1, and 21.1 g of phosphorus per kg of waste for cattle, swine, and poultry respectively, as reported by Barnett [108]. CO_2eq = carbon dioxide equivalent.

With an estimated production of 4002.62 Gg per year, Jalisco is the largest producer of livestock waste at a national level, compared to the waste production reported for the remaining 31 states [35]. From the estimated livestock waste total production, swine, poultry, and cattle production are responsible for 61%, 28%, and 11% of waste generated, respectively.

4. Discussion

The multi-criteria GIS methodology suggests that CADUs should be located in four clusters selected based on waste production and environmental features that favor pollutant distribution, which led to an evident conglomeration of LPUs in Jalisco's northeast region. This geographical area is located in the hydrological region of the Lerma-Santiago-Chapala basin. As previously discussed, the basin is undergoing eutrophication, which has been shown to be related to livestock production and agricultural practices [45,48]. The degree of eutrophication of water bodies was not a parameter for the selection of the clusters; however, the cluster analysis shows that the critical zones that were selected are also the ones with the highest levels of water pollution [47]. Although there are several other factors to consider, this can be strong evidence of the environmental damage that can be caused by poor livestock and agricultural management practices, since inadequate management is known to produce large quantities of nitrogen, phosphorus, and other nutrients that are key to eutrophication processes in water bodies [116]. The methodology presented in this study could be improved by including additional environmental, economic, and social parameters, as well as an economic optimization framework. A SWOT (strengths, weaknesses, opportunities and threats) analysis is presented for the methodology used in this study (Table 9).

Table 9. SWOT (strengths, weaknesses, opportunities and threats) analysis table.

	Favorable	Unfavorable
	Strengths	**Weaknesses**
Internal	It is a quantitative methodology that makes it possible to identify and classify LPU clusters in a given region in areas of high environmental risk and with the most viability for CADU implementation as a result of the weighted overlay analysis. The results not only indicate where resources are available based on spatial distribution, but also show where the best potential and priority locations should be located in the future.	The application of the methodology may be subjective (i.e., it requires the judgment of experts to select the parameters and to determine their weights). The analytic hierarchy process (AHP) may be used for selecting and weighting the parameters, thus reducing bias in decision-making.
	It is a flexible methodology that allows for the integration of a wide variety of environmental, economic, and social parameters to the spatial model to help determine the optimal sites for installing CADUs from a holistic perspective.	Other parameters may be considered for the analysis such as the proximity to the electric grid or to the road network, the preparedness of farmers to participate, spatial water pollution levels, and a number of local factors not included in this study. Additionally, the financial viability could be assessed with the use of an economic optimization framework.
	The mathematical models rely on actual farm data of location and headcount of LPUs as well as actual data of the hydrographic structure of Jalisco, the digital elevation model, and the location of urban communities.	Euclidean distance between the potential sites and the LPUs was used rather than the road network distance.
	This methodology is rooted in multicriteria evaluation integrated with a geographical information system (GIS). The methodology can be easily implemented with a medium level of GIS understanding.	Only livestock manure was used for the calculation of the biogas potential. Information regarding the spatial distribution of a wider range of substrates available in Jalisco for co-digestion could improve the estimation of the state's potential for biogas production.
	The application of this methodology has favorable repercussions in decision-making on environmental, social, health, and economic issues.	In this study only bibliographical considerations were used to determine the precise methanogenic potential and nitrogen and phosphorus digestate composition. Experimental studies using biodigesters at the laboratory and pilot levels must be carried out because substrates tend to be highly site-specific.
	The resulting graphical display is easily understandable for state/local governments and other parties interested in biogas energy potential, and it serves as guide for planning investment in any local region.	The amount of energy produced by the CADUs represents only 3.4–5.5% of the state's energy consumption, so its scope will probably only satisfy local energy demands. The results of this current study may be underestimated, being that the total headcount according to SADER (Agriculture and Rural Development Agency) is 3.22, 89.10, and 7.47 times higher for swine, cattle, and poultry, respectively. However, the data estimated by SADER lacks the LPU location information necessary for the spatial analysis.
	With the implementation of CADUs, more farms can use a large facility and economies of scale can be achieved. Farmers need new ways to comply with increasing federal and state regulation of animal wastes.	Potential stakeholders interested in the implementation will need the CADUs to be connected to the grid. Such a connection can be costly if locations are not close enough to the existing electrical grid. This parameter should be included for the weighted overlay analysis in future studies.

Table 9. *Cont.*

	Favorable	Unfavorable
	Opportunities	**Threats**
External	This methodology allows for a first approach to a future implementation. However, the participation of different stakeholders would be necessary for a refining phase.	A poor selection of the panel of experts defining and weighing the parameters can translate into misleading results with economic, social, and environmental consequences.
	A wider range of substrates could be included in the analysis, although a comprehensive assessment is required to understand how a wider range of local substrates and substrate mixtures would affect the overall biodigester operation.	If the information collected in the databases is not reliable, the level of uncertainty in the results increases markedly.
	The methodology can be easily adapted to other fields of application such as identifying sites for managing urban solid waste, siting collection centers and processing food surpluses, and locating sites for managing waste from the tequila industry, among others.	Transporting manure poses certain risks to the environment and public health such as spillage of liquid or solid manure due to filtering, overloading, blowing winds, or equipment breaking. Appropriate transportation techniques should be applied.
	The best practices for waste management should be encouraged at the municipal and intermunicipal level for recycling and energy recovery, to promote farmers to become more interested in its implementation.	It is important to visualize possible changes in energy policy at the federal level before deriving policy recommendations. Unfavorable electricity sale tariffs may become a disincentive for future development of CADUs.
	A broader benefit–cost analysis to determine the optimal locations based on the capacity of the CADUs should involve the comparison of benefits and costs associated with pollution, to compare the economic costs of implementing CADUs against the environment, and the health costs of not implementing them.	Biogas production requires facilities with personnel with medium to high levels of technological skills. A lack of trained personnel could be a problem for further project implementation.
	The state of Jalisco is the third largest consumer of electrical energy in Mexico with 13,476.20 GW/h and it generates only 12% of that amount. The production of energy through CADUs contributes to improving the energy sufficiency of the state [117].	

Jalisco produces only 12% of the energy the state requires, which means it is compelled to import 88% of its energy from neighboring states, like Nayarit [118]. The total energetic potential of Jalisco's livestock waste represents 3.4% or 5.5% of the total energetic consumption reported for Jalisco in 2016 [119], with 53.68 MW and 85.68 MW for the two scenarios presented, with 25% and 40% efficiency generation, respectively. By generating electric energy from livestock waste Jalisco can increase its energy production by 28.7% or 45.8% for these scenarios, respectively. This could add up to Jalisco producing a total of 15.45% or 17.5% of the energy it requires. The state has set the goal of producing 80% of its electrical energy demand by 2024 [119] and utilizing livestock waste as an energy source can help the state move closer to meeting this goal. Cluster C, which among the four identified clusters showed the highest energetic potential, has a total energetic potential calculated to be between 23 and 36.8 MW; that is, almost enough to cover 1.5% or 2.4% of Jalisco's energy demand. Comparing the results for the proposed A and B scenarios for energy generation calculations makes it clear that an estimated 62% increase in the overall energy generated can be achieved by increasing the conversion efficiency by using larger centralized generators rather than small-scale farm generators.

In addition to methane production and electricity generation, anaerobic digestion generates valuable digestate. Compared to crude untreated manure, this digestate contains different nitrogen and phosphorus compositions with higher availability for crops and presents higher sorption rates, mainly due to the fact that the forms and proportions in which they are present change during the AD process [33,34,120]. Moreover, since it is generated as a liquid sludge, it makes it possible to concentrate the nutrient load by humidity reduction and simplifies transportation and field application [121]. This liquid fertilizer offers better infiltration rates compared to compost and inorganic fertilizers by reducing nitrogen volatilization and improving crop nutrient absorption [122]. The total amount of nitrogen produced by the livestock industry of Jalisco is comparable to the estimated nitrogen required to fertilize Jalisco's cultivated land. The total nitrogen produced per year could be utilized to fertilize approximately 259,160 ha of maize fields [123]. While this might be promising, taking into consideration that the approximate area dedicated to maize cultivation alone is 7,441,000 ha [124] and almost 84% of the fertilizers needed at a national level must be imported [125], the field application of untreated livestock waste loses its economic advantage compared to inorganic fertilizers due to increasing transportation costs. Furthermore, it leads to the accumulation of waste in the fields surrounding LPUs [126]. Digestate produced by CADUs, on the other hand, makes it possible to reduce transportation and application costs compared to untreated livestock waste, while keeping production costs lower than those of inorganic fertilizers. The volume and mass reduction of digestate is key to making it easily transportable by reducing its bulk water content and concentrating its nutrients. Simple solid–liquid separation methods like screen separators offer low separation rates at low costs, whereas more advanced methods like screw pressing and decanter centrifugation offer better separation rates at higher costs. These separation methods might be favorable in the case of CADUs given that higher volumes of waste often reduce overall separation costs while maintaining separation rates [121]. Further humidity reduction can be achieved by a sequential drying process using waste-heat generated from the conversion of the chemical energy of biogas into electrical and mechanical energy. This would reduce transportation costs without greatly increasing treatment costs [121]. Multiple drying options have been developed to reduce the water content of the generated digestate in order to concentrate its nutrients and reduce transportation costs; belt drying, drum drying, and solar drying are some of the most commonly used methods, followed by thermal vaporization [127].

Multiple models for determining the viability of manure application as a substitute for inorganic fertilizer have been designed for high livestock waste-producing regions in order to prevent nutrient accumulation in nearby fields. The increase in transportation costs has been linked to the high volume of waste required to match the nutrient content of traditional inorganic fertilizers (since waste has a high humidity content), and even though manure is generally cheaper than inorganic fertilizers, transportation and application costs increase its total cost [128,129]. Jalisco's total phosphorus production has the potential to fertilize 519,228 ha of maize crop fields [130], but the same situation presented for nitrogen field application occurs, where transportation costs reduce its economic advantage in comparison to inorganic fertilizers when it is presented as untreated manure.

Another benefit resulting from the revalorization of waste by anaerobic digestion is a significant reduction in CO_2eq emissions, since the controlled digestion of livestock waste reduces the emission of CH_4 and NO_x gases to the atmosphere. Treating Jalisco's livestock waste through anaerobic digestion—in conjunction with its revalorization as an energy source—can amount to a reduction of almost 89.8% in the state's total livestock emissions. The total emission estimated for Jalisco's livestock production industry matches the figures reported by SEMADET [131]. This potential reduction in CO_2eq generation would represent 10.5% of the state's total greenhouse gas emissions, which would move the state closer to its goal of 22% reduction in greenhouse gas emissions set for the year 2030 [42]. Comparing the greenhouse gas emissions calculation for the proposed A and B scenarios, there is an overall 9.6-fold reduction in emissions if CADUs are implemented (in comparison to direct field application). This can be attributed to the controlled anaerobic degradation conditions during the AD process in which N_2O emissions are greatly reduced. Additionally, the methane generated is transformed into CO_2 by combustion during the energy generation process [112–114].

Compared to the data reported by SADER (Agriculture and Rural Development Agency) and used by Hernandez-De Lira [35], the total headcount for Jalisco reported in the databases used in this study is significantly lower, as the data from this study come from official state waste generation records of registered producers and most small and micro-scale producers are not included in the records. Another significant difference with the data used by Hernandez-De Lira [35] is that the total headcount and waste inventory are calculated at a state level, based on municipal data rather than based on individual values for each LPU. Multiple LPU-dependent parameters cannot be determined at the municipal level, such as the distance between runoffs and farms, and between farms and possible CADUs.

This discrepancy between the inventories reported by SADER and SEMADET-ANBIO could indicate that the results of this current study are underestimated, being that the total headcount according to SADER is 3.22, 89.10, and 7.47 times higher for swine, cattle, and poultry respectively. Following the proposed methodology using the state headcount data from SADER, an estimate can be calculated which results in a total waste generation value 13.81 times higher, and an energetic potential 10.86 times higher than the one estimated in this study using SEMADET-ANBIO data. This could point to a higher risk of pollution and higher greenhouse gas emission generation but could also offer a more significant opportunity for the implementation of large-scale CADUs and a greater contribution to the energetic potential of the state.

Despite the viability in terms of biomass, biogas, and energy potential, the appropriate implementation of biodigesters requires the development of external strategies such as social engineering, logistics, and public health. Transportation, efficiency, and especially, public health matters are crucial considerations for the viability of implementation [132]. Many cluster-based studies have focused on the distances to energy transmission lines, roadmaps, and routes, in order to create a model that is closer to waste management reality [22,57,58,75], yet very few studies have actually considered the sanitary and public health aspects of transporting untreated manure [133]. The risk of pathogen transmission is increased by the lack of sanitary precautions, which can lead to serious health hazards for livestock and humans [134]. In order to design an potential integral economic and environmental vision for the future, the matters of possible markets, demand, supply, and transportation must be considered [133]. In order to make this a reality, it is crucial that planning and urban development professionals and local authorities be involved in health and management determinants [132].

Currently there is little information about the costs of large facilities producing biogas from agricultural wastes and/or livestock manure in Mexico, although the experiences reported in several publications show that the technology is at a high level of maturity. Enterprises like Agraferm (Germany), Zorg Biogas (Germany), or Weltech Biopower (Germany) are some examples of companies leading in the development of technology and have reported several success stories around the world [135–137]. On the other hand, reports out of China point at problems such as inferior equipment technology and imperfect policy incentives that hamper the widespread application and promotion of biogas production from livestock manure. With the rapid development of the economy and the improvement of rural living conditions, the Chinese biogas industry is expected to move quickly toward escalation, industrialization, and commercialization [138]. In the case of Mexico, estimates of methane emission factors from cattle manure have already been reported by González-Avalos and Ruiz-Suárez [139], and Rendón-Huerta et al. [140] reported trends in greenhouse gas emissions from dairy cattle in Mexico between 1970 and 2010 [139]. These figures show the continuous growth of the cattle business in Mexico in the last 20 years. Given that Jalisco is the national leader in food production, we consider it would be very relevant for the state to analyze the potential for reducing greenhouse gas emissions from livestock manure while producing energy and eco-friendly fertilizers for agriculture. The first step in this direction is to identify the areas of major interest to locate the CADUs in the state of Jalisco. As a second step, this information must be refined with the participation of different stakeholders such as the Secretary of Environment and Territorial Development, the Secretary of Agriculture and Rural Development, and the State Energy Agency, as well as different farmers and livestock producers' associations. The Secretary of Environment and Territorial Development is in charge of the management of waste that results from the productive sector [141] and in collaboration with the Secretary of Agriculture and Rural Development has the ability to develop a program and establish regulations to ensure the best waste management practices [142]. The State Energy Agency incentivizes the generation of green energy in order to fulfill the state's energetic needs [143]. Establishing a dialogue between these three main state government players can offer better insights and opportunities for further development of the proposed model in the near future as the state is focused on reducing waste generation and greenhouse gas emissions and increasing energy sufficiency.

Based on the experiences reported from other countries, the main hurdles that Mexico could face in implementing this strategy could be: (a) the reliability of the technology [138,144]; (b) capacity building for the management of biogas production technologies [144,145]; (c) a dearth of public resources to promote the implementation of these technologies; (d) the development of a private-public participation scheme to include government, farmers, and technology developers in the businesses model [146]; (e) the implementation of a legal framework at the federal level that permits the production and utilization of alternative energy to reduce the country's dependence on fossil fuels [147]; (f) more efficient utilization of biogas to channel it into the natural gas grid [148]; and (g) the model should avoid causing increases in energy demand, competition for land, agricultural prices, and production costs for livestock [148].

5. Conclusions

Jalisco is the largest producer of livestock and agricultural products, and their respective waste, in Mexico. The electric potential derived from the livestock waste generated in Jalisco calculated in this study ranged from 53.63 MW to 85.88 MW, depending on the conversion efficiency of the generators used; this corresponds to 3.4% or 5.5% of the total electrical energy demand of Jalisco, respectively. The nitrogen and phosphorus production values calculated for the state were 49.2 Gg and 31.1 Gg, respectively. The implementation of at least one of the proposed clusters can reduce a minimum of 259.6 Gg of CO_2eq; that is, 1% of the total carbon footprint of Jalisco.

Implementing waste treatment clusters also offers small- and medium-sized producers the opportunity to revalorize their waste and decrease their environmental impact by reducing nitrogen, phosphorus, and greenhouse gas emissions. Additionally, it provides pathways to decreasing treatment costs by simultaneously generating energy and high demand products like fertilizers.

The proposed methodology can be implemented in other livestock-intensive regions in order to identify and select critical regions and clusters for the management of livestock waste, given that several livestock-producing regions are known to face similar problems as Jalisco.

To improve the proposed methodology, more information about transportation costs (for transporting substrates from the LPUs to the CADUs and transporting digestates from the CADUs to the final consumers) could be included in the spatial analysis, in order to factor them into the model. Additionally, information regarding the spatial distribution of a wider range of substrates available in Jalisco for co-digestion could improve the estimates of the state's potential for biogas production, especially considering that Jalisco is known as Mexico's "agri-food giant" as some of its main agricultural products are sugar cane, corn, and agave. Therefore, further studies examining not only livestock waste, but local agricultural and food waste as well, could be carried out using the proposed methodology to identify critical waste generation zones and propose revalorization and treatment technologies that integrate social engineering, logistics, and public health policies to reduce the environmental impact of agriculture and food production in Jalisco. Furthermore, experimental studies at the laboratory and pilot levels using biodigesters and different mixtures of local substrates must be carried out to determine the precise methanogenic potential of substrates and the nutrient composition of the digestates.

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References

1. Jongbloed, A.W.; Lenis, N.P. Environmental concerns about animal manure. *J. Anim. Sci.* **1998**, *76*, 2641–2648. [CrossRef] [PubMed]
2. Manyi-Loh, C.E.; Mamphweli, S.N.; Meyer, E.L.; Makaka, G.; Simon, M.; Okoh, A.I. An Overview of the Control of Bacterial Pathogens in Cattle Manure. *Int. J. Environ. Res. Public Health* **2016**, *13*, 843. [CrossRef] [PubMed]
3. Sun, B.; Zhang, L.; Yang, L.; Zhang, F.; Norse, D.; Zhu, Z. Agricultural Non-Point Source Pollution in China: Causes and Mitigation Measures. *AMBIO* **2012**, *41*, 370–379. [CrossRef] [PubMed]
4. Hölzel, C.S.; Müller, C.; Harms, K.S.; Mikolajewski, S.; Schäfer, S.; Schwaiger, K.; Bauer, J. Heavy metals in liquid pig manure in light of bacterial antimicrobial resistance. *Environ. Res.* **2012**, *113*, 21–27. [CrossRef]
5. Ul Islam, E.; Yang, X.; He, Z.; Mahmood, Q. Assessing potential dietary toxicity of heavy metals in selected vegetables and food crops. *J. Zhejiang Univ. Sci. B* **2007**, *8*, 1–13. [CrossRef]
6. Demirel, B.; Göl, N.P.; Onay, T.T. Evaluation of heavy metal content in digestate from batch anaerobic co-digestion of sunflower hulls and poultry manure. *J. Mater. Cycles Waste Manag.* **2013**, *15*, 242–246. [CrossRef]
7. Sun, C.; Wu, H. Assessment of pollution from livestock and poultry breeding in China. *Int. J. Environ. Stud.* **2013**, *70*, 232–240. [CrossRef]
8. Wolter, M.; Prayitno, S.; Schuchardt, F. Greenhouse gas emission during storage of pig manure on a pilot scale. *Bioresour. Technol.* **2004**, *95*, 235–244. [CrossRef]
9. Bandara, N.J.G.J.; Hettiarachchi, P.J. Environmental Impacts Associated with Current Waste Disposal Practices in a Municipality in Sri Lanka—A Case Study. *Int. J. Environ. Waste Manag.* **2010**. [CrossRef]

10. Spencer, J.L.; Guan, J. Public Health Implications Related to Spread of Pathogens in Manure From Livestock and Poultry Operations. In *Public Health Microbiology: Methods and Protocols*; Spencer, J.F.T., Ragout de Spencer, A.L., Eds.; Methods in Molecular Biology; Humana Press: Totowa, NJ, USA, 2004; pp. 503–515, ISBN 978-1-59259-766-6.
11. Seltenrich, N. Manure Irrigation: Environmental Benefits, Potential Human Health Risks. *Environ. Health Perspect.* **2017**, *125*, 124004. [CrossRef]
12. Sahoo, P.K.; Kim, K.; Powell, M.A. Managing Groundwater Nitrate Contamination from Livestock Farms: Implication for Nitrate Management Guidelines. *Curr. Pollut. Rep.* **2016**, *2*, 178–187. [CrossRef]
13. Magrí, A.; Teira-Esmatges, M.R. Assessment of a composting process for the treatment of beef cattle manure. *J. Environ. Sci. Health Part B* **2015**, *50*, 430–438. [CrossRef] [PubMed]
14. Peigné, J.; Girardin, P. Environmental Impacts of Farm-Scale Composting Practices. *Water Air Soil Pollut.* **2004**, *153*, 45–68. [CrossRef]
15. Bilgili, M.S.; Demir, A.; Özkaya, B. Influence of leachate recirculation on aerobic and anaerobic decomposition of solid wastes. *J. Hazard. Mater.* **2007**, *143*, 177–183. [CrossRef] [PubMed]
16. SEMADET. Listados de las Cédulas de Operación Annual. Available online: https://semadet.jalisco.gob.mx/medio-ambiente/calidad-del-aire/listados-de-las-cedulas-de-operacion-anual (accessed on 7 January 2019).
17. Gumisiriza, R.; Hawumba, J.F.; Okure, M.; Hensel, O. Biomass waste-to-energy valorisation technologies: A review case for banana processing in Uganda. *Biotechnol. Biofuels* **2017**, *10*, 11. [CrossRef] [PubMed]
18. Rabii, A.; Aldin, S.; Dahman, Y.; Elbeshbishy, E. A Review on Anaerobic Co-Digestion with a Focus on the Microbial Populations and the Effect of Multi-Stage Digester Configuration. *Energies* **2019**, *12*, 1106. [CrossRef]
19. Huang, H.; Tang, L. Treatment of organic waste using thermal plasma pyrolysis technology. *Energy Convers. Manag.* **2007**, *48*, 1331–1337. [CrossRef]
20. Tsydenova, N.; Vázquez Morillas, A.; Martínez Hernández, Á.; Rodríguez Soria, D.; Wilches, C.; Pehlken, A. Feasibility and Barriers for Anaerobic Digestion in Mexico City. *Sustainability* **2019**, *11*, 4114. [CrossRef]
21. Batzias, F.A.; Sidiras, D.K.; Spyrou, E.K. Evaluating livestock manures for biogas production: a GIS based method. *Renew. Energy* **2005**, *30*, 1161–1176. [CrossRef]
22. Ma, J.; Scott, N.R.; DeGloria, S.D.; Lembo, A.J. Siting analysis of farm-based centralized anaerobic digester systems for distributed generation using GIS. *Biomass Bioenergy* **2005**, *28*, 591–600. [CrossRef]
23. Shammas, N.K.; Wang, L.K. Aerobic Digestion. In *Biosolids Treatment Processes*; Wang, L.K., Shammas, N.K., Hung, Y.-T., Eds.; Handbook of Environmental Engineering; Humana Press: Totowa, NJ, USA, 2007; pp. 177–205, ISBN 978-1-59259-996-7.
24. Campbell, H.W.; Bridle, T.R. Sludge management by thermal conversion to fuels. *Can. J. Civ. Eng.* **1986**, *13*, 569–574. [CrossRef]
25. Cantrell, K.B.; Ducey, T.; Ro, K.S.; Hunt, P.G. Livestock waste-to-bioenergy generation opportunities. *Bioresour. Technol.* **2008**, *99*, 7941–7953. [CrossRef] [PubMed]
26. Ciuta, S.; Tsiamis, D.; Castaldi, M.J. *Gasification of Waste Materials: Technologies for Generating Energy, Gas, and Chemicals from Municipal Solid Waste, Biomass, Nonrecycled Plastics, Sludges, and Wet Solid Wastes*; Academic Press: Cambridge, MA, USA, 2017; ISBN 978-0-12-812717-9.
27. Leip, A.; Ledgard, S.; Uwizeye, A.; Palhares, J.C.P.; Aller, M.F.; Amon, B.; Binder, M.; Cordovil, C.M.D.S.; De Camillis, C.; Dong, H.; et al. The value of manure—Manure as co-product in life cycle assessment. *J. Environ. Manag.* **2019**, *241*, 293–304. [CrossRef] [PubMed]
28. Zeeman, G.; Gerbens, S. CH4 Emissions from Animal Manure. Available online: https://research.wur.nl/en/publications/ch4-emissions-from-animal-manure (accessed on 11 March 2020).
29. Daniel-Gromke, J.; Rensberg, N.; Denysenko, V.; Stinner, W.; Schmalfuß, T.; Scheftelowitz, M.; Nelles, M.; Liebetrau, J. Current Developments in Production and Utilization of Biogas and Biomethane in Germany. *Chem. Ing. Tech.* **2018**, *90*, 17–35. [CrossRef]
30. Uggetti, E.; Sialve, B.; Latrille, E.; Steyer, J.-P. Anaerobic digestate as substrate for microalgae culture: The role of ammonium concentration on the microalgae productivity. *Bioresour. Technol.* **2014**, *152*, 437–443. [CrossRef]
31. Michelon, W.; Da Silva, M.L.B.; Mezzari, M.P.; Pirolli, M.; Prandini, J.M.; Soares, H.M. Effects of Nitrogen and Phosphorus on Biochemical Composition of Microalgae Polyculture Harvested from Phycoremediation of Piggery Wastewater Digestate. *Appl. Biochem. Biotechnol.* **2016**, *178*, 1407–1419. [CrossRef]

32. Cavalli, D.; Cabassi, G.; Borrelli, L.; Geromel, G.; Bechini, L.; Degano, L.; Marino Gallina, P. Nitrogen fertilizer replacement value of undigested liquid cattle manure and digestates. *Eur. J. Agron.* **2016**, *73*, 34–41. [CrossRef]
33. Fernando, W.A.R.N.; Xia, K.; Rice, C.W. Sorption and Desorption of Ammonium from Liquid Swine Waste in Soils. *Soil Sci. Soc. Am. J.* **2005**, *69*, 1057–1065. [CrossRef]
34. Reisenauer, H.M. Absorption and utilization of ammonium nitrogen by plants. In *Soil–Plant–Nitrogen Relationships*; Nielsen, D.R., MacDonald, J.G., Eds.; Academic Press: Cambridge, MA, USA, 1978; pp. 157–170, ISBN 978-0-12-518402-1.
35. Hernandez-De Lira, I.O.; Huber, D.H.; Espinosa-Solares, T.; Balagurusamy, N. Methane emission and bioenergy potential from livestock manures in Mexico. *J. Renew. Sustain. Energy* **2015**, *7*, 053117. [CrossRef]
36. Ávalos, E.G.; Suárez, L.G.R. Methane conversion factors from cattle manure in México. *Atmósfera* **2009**, *20*.
37. Losada, H.; Cortes, J.; Rivera, J.; Vargas, J. Recycling of solid wastes in Mexico City in livestock and agricultural production systems as a sustainable alternative. *Field Actions Sci. Rep. J. Field Actions* **2011**, *5*, 1–11.
38. Garcia, G.; Rueda, J.C. Reporte Mexicano de Cambio Climático. Available online: http://www.pincc.unam.mx/libro_reportemex/reporte_mexicano_vol_III.pdf (accessed on 13 March 2020).
39. Instituto Nacional de Ecología y Cambio Inventario Nacional de Emisiones de Gases y Compuestos de Efecto Invernadero. Available online: http://www.gob.mx/inecc/acciones-y-programas/inventario-nacional-de-emisiones-de-gases-y-compuestos-de-efecto-invernadero (accessed on 10 March 2020).
40. Secrearia de Medio Ambiente y Recursos Naturales. Soil Degradation in Mexico. Available online: https://apps1.semarnat.gob.mx:8443/dgeia/informe_2008_ing/03_suelos/cap3_2.html (accessed on 10 March 2020).
41. Herrera, I.M.R.; Castañeda, M.G.; Robles, J.; León, J.F. Development of the Health Atlas of Jalisco: A New Web-Based Service for the Ministry of Health and the Community in Mexico. *JMIR Public Health Surveill.* **2016**, *2*, e11. [CrossRef] [PubMed]
42. Instituto Nacional de Ecología y Cambio. INECC Reitera su Compromiso Ante el Acuerdo de París con Rutas de Mitigación al Cambio Climático. Available online: http://www.gob.mx/inecc/prensa/inecc-reitera-su-compromiso-ante-el-acuerdo-de-paris-con-rutas-de-mitigacion-al-cambio-climatico (accessed on 10 March 2020).
43. INEGI. Encuesta Nacional Agropecuaria 2017. Available online: https://www.inegi.org.mx/programas/ena/2017/default.html#Tabulados (accessed on 10 March 2020).
44. DOF. Norma Oficial Mexicana NOM-161-SEMARNAT-2011. Available online: http://dof.gob.mx/nota_detalle.php?codigo=5286505&fecha=01/02/2013 (accessed on 11 March 2020).
45. De Anda, J.; Shear, H. Nutrients and Eutrophication in Lake Chapala. In *The Lerma-Chapala Watershed: Evaluation and Management*; Hansen, A.M., van Afferden, M., Eds.; Springer US: Boston, MA, USA, 2001; pp. 183–198, ISBN 978-1-4615-0545-7.
46. CONAGUA. Statistics on Water in Mexico 2005. Available online: http://www.conagua.gob.mx/CONAGUA07/Publicaciones/Publicaciones/EAM2015_ing.pdf (accessed on 13 March 2020).
47. Sedeño-Díaz, J.E.; López-López, E. Water Quality in the Río Lerma, Mexico: An Overview of the Last Quarter of the Twentieth Century. *Water Resour. Manag.* **2007**, *21*, 1797–1812. [CrossRef]
48. López-Hernández, M.; Ramos-Espinosa, M.G.; Carranza-Fraser, J. Análisis multimétrico para evaluar contaminación en el río Lerma y lago de Chapala, México. *Hidrobiológica* **2007**, *17*, 17–30.
49. Kramer, D.L. Dissolved oxygen and fish behavior. *Environ. Biol. Fishes* **1987**, *18*, 81–92. [CrossRef]
50. Shortle, J.S.; Abler, D.G. *Environmental Policies for Agricultural Pollution Control*; CABI: New York, NY, USA, 2001; ISBN 978-0-85199-779-7.
51. Laws, E.A. *Aquatic Pollution: An Introductory Text*; John Wiley & Sons: New York, NY, USA, 2017; ISBN 978-1-119-30450-0.
52. De Anda, J.; Gradilla-Hernández, M.S.; Díaz-Torres, O.; de Jesús Díaz-Torres, J.; de la Torre-Castro, L.M. Assessment of heavy metals in the surface sediments and sediment-water interface of Lake Cajititlán, Mexico. *Environ. Monit. Assess.* **2019**, *191*, 396. [CrossRef]
53. De Anda, J.; de Jesús Díaz-Torres, J.; Gradilla-Hernández, M.S.; de la Torre-Castro, L.M. Morphometric and water quality features of Lake Cajititlán, Mexico. *Environ. Monit. Assess.* **2019**, *191*, 92. [CrossRef]
54. Ortiz-Jiménez, M.A.; De Anda, J.; Shear, H. Nutrients/food chain model for Lake Zapotlan (Mexico). *Int. J. River Basin Manag.* **2006**, *4*, 125–135. [CrossRef]

55. Montoya, H.A.; Contreras, C.S.; Garcia, V.M. *Estudio Integral de la Calidad del Agua en el Estado de Jalisco*; Comisión Nacional del Agua: Guadalajara, Mexico, 1997; p. 106.
56. Venier, F.; Yabar, H. Renewable energy recovery potential towards sustainable cattle manure management in Buenos Aires Province: Site selection based on GIS spatial analysis and statistics. *J. Clean. Prod.* **2017**, *162*, 1317–1333. [CrossRef]
57. Thompson, E.; Wang, Q.; Li, M. Anaerobic digester systems (ADS) for multiple dairy farms: A GIS analysis for optimal site selection. *Energy Policy* **2013**, *61*, 114–124. [CrossRef]
58. Dagnall, S.; Hill, J.; Pegg, D. Resource mapping and analysis of farm livestock manures—Assessing the opportunities for biomass-to-energy schemes. *Bioresour. Technol.* **2000**, *71*, 225–234. [CrossRef]
59. Höhn, J.; Lehtonen, E.; Rasi, S.; Rintala, J. A Geographical Information System (GIS) based methodology for determination of potential biomasses and sites for biogas plants in southern Finland. *Appl. Energy* **2014**, *113*, 1–10. [CrossRef]
60. 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]
61. Brahma, A.; Saikia, K.; Hiloidhari, M.; Baruah, D.C. GIS based planning of a biomethanation power plant in Assam, India. *Renew. Sustain. Energy Rev.* **2016**, *62*, 596–608. [CrossRef]
62. Delivand, M.K.; Cammerino, A.R.B.; Garofalo, P.; Monteleone, M. Optimal locations of bioenergy facilities, biomass spatial availability, logistics costs and GHG (greenhouse gas) emissions: a case study on electricity productions in South Italy. *J. Clean. Prod.* **2015**, *99*, 129–139. [CrossRef]
63. Osei, E.; Gassman, P.W.; Hauck, L.M.; Neitsch, S.; Jones, R.D.; McNitt, J.; Jones, H. Economic and Environmental Impacts of Pasture Nutrient Management. *J. Range Manag.* **2003**, *56*, 218–226. [CrossRef]
64. Wardropper, C.B.; Chang, C.; Rissman, A.R. Fragmented water quality governance: Constraints to spatial targeting for nutrient reduction in a Midwestern USA watershed. *Landsc. Urban Plan.* **2015**, *137*, 64–75. [CrossRef]
65. Sharara, M.; Sampat, A.; Good, L.W.; Smith, A.S.; Porter, P.; Zavala, V.M.; Larson, R.; Runge, T. Spatially explicit methodology for coordinated manure management in shared watersheds. *J. Environ. Manag.* **2017**, *192*, 48–56. [CrossRef] [PubMed]
66. Roubík, H.; Mazancová, J.; Phung, L.D.; Banout, J. Current approach to manure management for small-scale Southeast Asian farmers—Using Vietnamese biogas and non-biogas farms as an example. *Renew. Energy* **2018**, *115*, 362–370. [CrossRef]
67. Pukšec, T.; Duić, N. Economic viability and geographic distribution of centralized biogas plants: Case study Croatia. *Clean Technol. Environ. Policy* **2012**, *14*, 427–433. [CrossRef]
68. INEGI. Continuo de Elevaciones Mexicano (CEM). Available online: https://www.inegi.org.mx/app/geo2/elevacionesmex/ (accessed on 10 March 2020).
69. Tomlinson, R.F. Geographic Information Systems—A New Frontier. Available online: https://www.taylorfrancis.com/ (accessed on 10 March 2020).
70. Downey, I.; Heywood, I.; Petch, J. Landscape Ecology as an Operational Framework for Environmental GIS: Zdarske Vrchy, Czechoslovakia. In *Systems Thinking in Europe*; Jackson, M.C., Mansell, G.J., Flood, R.L., Blackham, R.B., Probert, S.V.E., Eds.; Springer US: Boston, MA, USA, 1991; pp. 151–158, ISBN 978-1-4615-3748-9.
71. Ramachandra, T.V. Geographical Information System Approach for Regional Biogas Potential Assessment. *Res. J. Environ. Sci.* **2008**, *2*, 170–184. [CrossRef]
72. ESRI. Producir un Análisis de Cluster, Clases y Archivos de Firma—Ayuda | ArcGIS for Desktop. Available online: https://desktop.arcgis.com/es/arcmap/10.3/tools/spatial-analyst-toolbox/producing-signature-files-class-and-cluster-analysis.htm (accessed on 5 April 2020).
73. Mukherjee, D.; Cromley, R.G.; Shah, F.A.; Bravo-Ureta, B.E. Optimal location of centralized biodigesters for small dairy farms: A case study from the United States. *Int. J. Sustain. Energy Plan. Manag.* **2015**, *8*, 3–16. [CrossRef]
74. Comber, A.; Dickie, J.; Jarvis, C.; Phillips, M.; Tansey, K. Locating bioenergy facilities using a modified GIS-based location–allocation-algorithm: Considering the spatial distribution of resource supply. *Appl. Energy* **2015**, *154*, 309–316. [CrossRef]
75. Zareei, S. Evaluation of biogas potential from livestock manures and rural wastes using GIS in Iran. *Renew. Energy* **2018**, *118*, 351–356. [CrossRef]

76. Zubaryeva, A.; Zaccarelli, N.; Del Giudice, C.; Zurlini, G. Spatially explicit assessment of local biomass availability for distributed biogas production via anaerobic co-digestion—Mediterranean case study. *Renew. Energy* **2012**, *39*, 261–270. [CrossRef]
77. Manfredi, S.; Pant, R.; Pennington, D.W.; Versmann, A. Supporting environmentally sound decisions for waste management with LCT and LCA. *Int. J. Life Cycle Assess.* **2011**, *16*, 937–939. [CrossRef]
78. Mutz, D.; Hengevoss, D.; Hugi, C.; Gross, T. Waste-to-Energy Options in Municipal Solid Waste Management A Guide for Decision Makers in Developing and Emerging Countries. 2017. Available online: https://irf.fhnw.ch/handle/11654/25779 (accessed on 10 March 2020).
79. United States Department of Agriculture. Animal Manure Management. Available online: https://www.nrcs.usda.gov/wps/portal/nrcs/detail/null/?cid=nrcs143_014211 (accessed on 13 March 2020).
80. Loyon, L. Overview of Animal Manure Management for Beef, Pig, and Poultry Farms in France. *Front. Sustain. Food Syst.* **2018**, *2*. [CrossRef]
81. Lander, C.H. *RCA III, Nutrient Use in Cropland Agriculture (Commercial Fertilizer and Manure): Nitrogen and Phosphorus*; U.S. Department of Agriculture, NRCS: Washington, DC, USA, 1996.
82. Agencia Extremeña de la Energía. Los Residuos Ganaderos. Available online: https://www.agenex.net/images/stories/deptos/los-residuos-ganaderos.pdf (accessed on 13 March 2020).
83. Williamson, J.; Lingenfelter, D. *The Penn State Agronomy Guide*; Penn State University: State College, PA, USA, 2019.
84. Lorimor, J.; Powers, W. Manure Characteristics: Manure Management Systems Series 2004. Available online: https://www.canr.msu.edu/uploads/files/ManureCharacteristicsMWPS-18_1.pdf (accessed on 12 March 2020).
85. Fedler, C. Integration of Gasification for Processing Biomass Residuals. 2006. Available online: https://www.researchgate.net/publication/271431565_Integration_of_Gasification_for_Processing_Biomass_Residuals (accessed on 13 March 2020).
86. North Carolina State University. North Carolina Agricultural Chemicals Manual 2020. Available online: https://content.ces.ncsu.edu/north-carolina-agricultural-chemicals-manual (accessed on 13 March 2020).
87. Avan, H.; Karaman, S. Assessment of biogas production potential of livestock wastes in Tokat Province by geographic information systems (GIS) technologies. *Gaziosmanpasa Üniversitesi Ziraat Fakültesi Derg.* **2016**, *33*, 25–32.
88. Yazdani, M.; Monavari, S.M.; Omrani, G.A.; Shariat, M.; Hosseini, S.M. Landfill site suitability assessment by means of geographic information system analysis. *Solid Earth* **2015**, *6*, 945–956. [CrossRef]
89. Wachira, P.M.; Kimenju, J.W.; Wango, T.J.; Matheri, J.N. Solid Waste Dumping Site Selection Using GIS and Remote Sensing for Kajiado County, Kenya. *J. Earth Sci. Eng.* **2014**, *4*, 693–702.
90. SEMARNAT. Animal Waste Management Methane Emissions 2008. Available online: https://www.globalmethane.org/documents/ag_cap_mexico.pdf (accessed on 10 March 2020).
91. OECD. *Ministry of Economy of Mexico Market Examinations in Mexico: Case Study of the Pork Meat Market 2019*; OECD: Paris, France, 2019.
92. Mohammed, H.I.; Majid, Z.; Yamusa, Y.B. GIS based sanitary landfill suitability analysis for sustainable solid waste disposal. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *220*, 012056. [CrossRef]
93. Khan, D.; Samadder, S.R. A simplified multi-criteria evaluation model for landfill site ranking and selection based on AHP and GIS. *J. Environ. Eng. Landsc. Manag.* **2015**, *23*, 267–278. [CrossRef]
94. Fiume, E.L. *The Mathematical Structure of Raster Graphics*; Academic Press: Cambridge, MA, USA, 2014; ISBN 978-1-4832-6082-2.
95. Horn, B.K.P. Hill shading and the reflectance map. *Proc. IEEE* **1981**, *69*, 14–47. [CrossRef]
96. Al-Hanbali, A.; Alsaaideh, B.; Kondoh, A. Using GIS-Based Weighted Linear Combination Analysis and Remote Sensing Techniques to Select Optimum Solid Waste Disposal Sites within Mafraq City, Jordan. *J. Geogr. Inf. Syst.* **2011**, *03*, 267. [CrossRef]
97. Vaissi, S.; Sharifi, M. Integrating multi-criteria decision analysis with a GIS-based siting procedure to select a protected area for the Kaiser's mountain newt, Neurergus kaiseri (Caudata: Salamandridae). *Glob. Ecol. Conserv.* **2019**, *20*, e00738. [CrossRef]
98. Yager, R.R. On ordered weighted averaging aggregation operators in multicriteria decisionmaking. *IEEE Trans. Syst. Man Cybern.* **1988**, *18*, 183–190. [CrossRef]

99. American Society of Agricultural Engineers Manure Production and Characteristics 2003. Available online: http://large.stanford.edu/publications/power/references/docs/ASAEStandard.pdf (accessed on 23 February 2020).
100. Olaya-Arboleda, Y.; Gonzales, L.O. FUNDAMENTOS PARA EL DISEÑO DE BIODIGESTORES 2009. Available online: http://www.bdigital.unal.edu.co/7967/4/luisoctaviogonzalezsalcedo.20121.pdf (accessed on 13 March 2020).
101. Li, Y.; Zhang, R.; Liu, G.; Chen, C.; He, Y.; Liu, X. Comparison of methane production potential, biodegradability, and kinetics of different organic substrates. *Bioresour. Technol.* **2013**, *149*, 565–569. [CrossRef]
102. Moody, L.B.; Burns, R.T.; Bishop, G.; Sell, S.T.; Spajic, R. Spajic Using Biochemical Methane Potential Assays to Aid in Co-substrate Selection for Co-digestion. *Appl. Eng. Agric.* **2011**, *27*, 433–439. [CrossRef]
103. Matulaitis, R.; Juškiene, V.; Juška, R. Measurement of methane production from pig and cattle manure in Lithuania. *Metano Emisijos iš Kiauliu ir Galviju Mešlo Matavimai Lietuvoje* **2015**. [CrossRef]
104. Marañón, E.; Castrillón, L.; Quiroga, G.; Fernández-Nava, Y.; Gómez, L.; García, M.M. Co-digestion of cattle manure with food waste and sludge to increase biogas production. *Waste Manag.* **2012**, *32*, 1821–1825. [CrossRef]
105. Dalkılıc, K.; Ugurlu, A. Biogas production from chicken manure at different organic loading rates in a mesophilic-thermopilic two stage anaerobic system. *J. Biosci. Bioeng.* **2015**, *120*, 315–322. [CrossRef] [PubMed]
106. Vodounnou, D.S.J.V.; Kpogue, D.N.S.; Tossavi, C.E.; Mennsah, G.A.; Fiogbe, E.D. Effect of animal waste and vegetable compost on production and growth of earthworm (Eisenia fetida) during vermiculture. *Int. J. Recycl. Org. Waste Agric.* **2016**, *5*, 87–92. [CrossRef]
107. Kirchmann, H.; Witter, E. Composition of fresh, aerobic and anaerobic farm animal dungs. *Bioresour. Technol.* **1992**, *40*, 137–142. [CrossRef]
108. Barnett, G.M. Phosphorus forms in animal manure. *Bioresour. Technol.* **1994**, *49*, 139–147. [CrossRef]
109. Tafdrup, S. Viable energy production and waste recycling from anaerobic digestion of manure and other biomass materials. *Biomass Bioenergy* **1995**, *9*, 303–314. [CrossRef]
110. Cuéllar, A.D.; Webber, M.E. Cow power: The energy and emissions benefits of converting manure to biogas. *Environ. Res. Lett.* **2008**, *3*, 034002. [CrossRef]
111. Forster, P.; Ramaswamy, V.; Artaxo, P.; Berntsen, T.; Betts, R.; Fahey, D.W.; Haywood, J.; Lean, J.; Lowe, D.C.; Raga, G.; et al. Changes in Atmospheric Constituents and in Radiative Forcing 2007. Available online: http://www.cgd.ucar.edu/events/20130729/files/Forster-Ramaswamy-etal-2007.pdf (accessed on 2 February 2019).
112. Philibert, A.; Loyce, C.; Makowski, D. Quantifying Uncertainties in N2O Emission Due to N Fertilizer Application in Cultivated Areas. *PLoS ONE* **2012**, *7*, e50950. [CrossRef]
113. Kim, D.-G.; Hernandez-Ramirez, G.; Giltrap, D. Linear and nonlinear dependency of direct nitrous oxide emissions on fertilizer nitrogen input: A meta-analysis. *Agric. Ecosyst. Environ.* **2013**, *168*, 53–65. [CrossRef]
114. Shcherbak, I.; Millar, N.; Robertson, G.P. Global metaanalysis of the nonlinear response of soil nitrous oxide (N2O) emissions to fertilizer nitrogen. *Proc. Natl. Acad. Sci. USA* **2014**, *111*, 9199–9204. [CrossRef] [PubMed]
115. IPCC. CH4 AND N2O EMISSIONS FROM LIVESTOCK MANURE. Available online: https://www.ipcc-nggip.iges.or.jp/public/gp/bgp/4_2_CH4_and_N2O_Livestock_Manure.pdf (accessed on 7 April 2020).
116. Abrol, V.; Sharma, P. *Resource Management for Sustainable Agriculture*; BoD—Books on Demand: Norderstedt, Germany, 2012; ISBN 978-953-51-0808-5.
117. SEDECO. Plan Estatal de Energia Jalisco 2019. Available online: https://consulmex.sre.gob.mx/guangzhou/images/PDFpromocion/JAL_Energa.pdf (accessed on 7 April 2020).
118. SENER. Evaluación Rápida del Uso de la Energía, Guadalajara, Jalisco, México 2016. Available online: https://www.gob.mx/cms/uploads/attachment/file/171261/13__Guadalajara.pdf (accessed on 10 March 2020).
119. ITESO. Modelo de Gobernanza Energética para el Estado de Jalisco 2016. Available online: https://plan.jalisco.gob.mx/sites/default/files/2019-06/Diagnstico-integrado-Plan-Estatal-de-Gobernanza-y-Desarrollo-07062019.pdf (accessed on 13 March 2020).
120. Walsh, J.J.; Jones, D.L.; Edwards-Jones, G.; Williams, A.P. Replacing inorganic fertilizer with anaerobic digestate may maintain agricultural productivity at less environmental cost. *J. Plant Nutr. Soil Sci.* **2012**, *175*, 840–845. [CrossRef]

121. Maurer, C.; Müller, J. Ammonia (NH3) emissions during drying of untreated and dewatered biogas digestate in a hybrid waste-heat/solar dryer. *Eng. Life Sci.* **2012**, *12*, 321–326. [CrossRef]
122. Tambone, F.; Scaglia, B.; D'Imporzano, G.; Schievano, A.; Orzi, V.; Salati, S.; Adani, F. Assessing amendment and fertilizing properties of digestates from anaerobic digestion through a comparative study with digested sludge and compost. *Chemosphere* **2010**, *81*, 577–583. [CrossRef] [PubMed]
123. Infascelli, R.; Pelorosso, R.; Boccia, L. Spatial assessment of animal manure spreading and groundwater nitrate pollution. *Geospat. Health* **2009**, *4*, 27–38. [CrossRef] [PubMed]
124. SIAP. SAGARPA Atlas Agroalimentario 2018. Available online: https://nube.siap.gob.mx/gobmx_publicaciones_siap/pag/2018/Atlas-Agroalimentario-2018 (accessed on 13 March 2020).
125. SADER; SIAP. EXPECTATIVAS AGROALIMENTARIAS 2019. Available online: http://infosiap.siap.gob.mx/gobmx/Brochure%20Expectativas%202019.pdf (accessed on 13 March 2020).
126. Keplinger, K.O.; Hauck, L.M. The Economics of Manure Utilization: Model and Application. *J. Agric. Resour. Econ.* **2006**, *31*, 414–440.
127. Rehl, T.; Müller, J. Life cycle assessment of biogas digestate processing technologies. *Resour. Conserv. Recycl.* **2011**, *56*, 92–104. [CrossRef]
128. Flotats, X.; Bonmatí, A.; Fernández, B.; Magrí, A. Manure treatment technologies: On-farm versus centralized strategies. NE Spain as case study. *Bioresour. Technol.* **2009**, *100*, 5519–5526. [CrossRef]
129. Fealy, R.; Schröder, J.J. *Assessment of Manure Transport Distances and Their Impact on Economic and Energy Costs*; IFS: Greifswald, Germany, 2008; ISBN 978-0-85310-279-3.
130. FAO. *Fertilizer Use by Crop*; FAO Fertilizer and Plant Nutrition Bulletin; Food and Agriculture Organization of the United Nations: Rome, Italy, 2006; ISBN 978-92-5-105592-2.
131. Carbon Trust; SEMADET. Inventario Estatal de Emisiones de Gases y Compuestos de Efecto Invernadero 2014. Available online: https://semadet.jalisco.gob.mx/gobernanza-ambiental/cambio-climatico/inventario-de-compuestos-y-gases-de-efecto-invernadero-cygei (accessed on 13 March 2020).
132. Capolongo, S.; Battistella, A.; Buffoli, M.; Oppio, A. Healthy design for sustainable communities. *Ann. Ig. Med. Prev. E Comunita* **2011**, *23*, 43–53.
133. Hu, Y.; Cheng, H.; Tao, S. Environmental and human health challenges of industrial livestock and poultry farming in China and their mitigation. *Environ. Int.* **2017**, *107*, 111–130. [CrossRef]
134. Sekkin, S. *Livestock Science*; BoD—Books on Demand: Norderstedt, Germany, 2017; ISBN 978-953-51-2863-2.
135. Zorg Biogas AG Zorg Biogas AG | The Official Corporate Web Site. Available online: http://zorg-biogas.com/?lang=en (accessed on 7 April 2020).
136. Agraferm Economical Anaerobic Digestion (AD), Biogas, Biomethane and Waste Treatment Plants—Agraferm-Group. Available online: http://www.agraferm.com/en/home.html (accessed on 7 April 2020).
137. WELTEC BIOPOWER. Available online: https://www.weltec-biopower.com/ (accessed on 7 April 2020).
138. Chen, L.; Zhao, L.; Ren, C.; Wang, F. The progress and prospects of rural biogas production in China. *Energy Policy* **2012**, *51*, 58–63. [CrossRef]
139. González-Avalos, E.; Ruiz-Suárez, L.G. Methane emission factors from cattle manure in Mexico. *Bioresour. Technol.* **2001**, *80*, 63–71. [CrossRef]
140. Rendón-Huerta, J.A.; Pinos-Rodríguez, J.M.; García-López, J.C.; Yáñez-Estrada, L.G.; Kebreab, E. Trends in greenhouse gas emissions from dairy cattle in Mexico between 1970 and 2010. *Anim. Prod. Sci.* **2014**, *54*, 292–298. [CrossRef]
141. SEMADET Secretaría de Medio Ambiente y Desarrollo Territorial. Available online: https://www.jalisco.gob.mx/es/gobierno/dependencias/semadet (accessed on 10 April 2020).
142. SADER Secretaría de Agricultura y Desarrollo Rural. Available online: https://www.jalisco.gob.mx/gobierno/dependencias/sader (accessed on 10 April 2020).
143. AEEJ Agencia de Energía del Estado de Jalisco. Available online: https://www.jalisco.gob.mx/es/gobierno/organismos/60447 (accessed on 10 April 2020).
144. Amigun, B.; von Blottnitz, H. Capacity-cost and location-cost analyses for biogas plants in Africa. *Resour. Conserv. Recycl.* **2010**, *55*, 63–73. [CrossRef]
145. World Bank. CAPACITY BUILDING FOR THE RAPID COMMERCIALIZATION OF RENEWABLE ENERGY IN CHINA 2005. Available online: https://energypedia.info/images/0/03/China_Capacity_Building_for_the_Rapid_Commercialization_of_Renewable_Energy.pdf (accessed on 10 April 2020).

146. Carrosio, G. Energy production from biogas in the Italian countryside: Policies and organizational models. *Energy Policy* **2013**, *63*, 3–9. [CrossRef]
147. Chien Bong, C.P.; Ho, W.S.; Hashim, H.; Lim, J.S.; Ho, C.S.; Peng Tan, W.S.; Lee, C.T. Review on the renewable energy and solid waste management policies towards biogas development in Malaysia. *Renew. Sustain. Energy Rev.* **2017**, *70*, 988–998. [CrossRef]
148. Giulio Mela, G.C. How Distorting Policies Can Affect Energy Efficiency and Sustainability: The Case of Biogas Production in the Po Valley (Italy). Available online: http://agbioforum.org/v16n3/v16n3a03-mela.htm (accessed on 7 April 2020).