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Article

Mapping of Biomass Fluxes: A Method for Optimizing Biogas-Refinery of Livestock Effluents

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Abstract: This paper presents the topic of the management of livestock effluents and, therefore, nutrients (particularly N) in the framework of the biogas supply chain. The bio-refinery will be analyzed as a unique system, from the farm to the biomass produced and sent to anaerobic digestion, focusing on the fate/change of the flow of material and nutrients content through the system. Within four categories of farms considered in the article, integrated ones frequently have a breeding consistency from 90 to 320 heads, according to more extensive or intensive settings. These farms must manage from 3.62 to 12.81 m^3 day^{-1} of slurry and from 11.40 to 40.34 kg day^{-1} of nitrogen (N) as the sum of excreta from all herd categories. By selecting a hypo-protein diet, a reduction of 10% and 24% for total effluent amount and for N excreted, respectively, can be achieved. Nitrogen can be reduced up to 45% if the crude protein content is limited and a further 0.23% if animals of similar ages, weights and (or) production or management are grouped and fed according to specific requirements. Integrated farms can implement farming activity with biogas production, possibly adding agricultural residues to the anaerobically-digested biomass. Average biogas yields for cattle effluents range from 200 to 400 m^3 ton^{-1} VS (volatile solids). Values from 320 to 672 m^3 day^{-1} of biogas can be produced, obtaining average values from 26 to 54.5 kWe (kilowatt-electric). This type of farm can well balance farm-production profit, environmental protection, animal husbandry well-being and energy self-sufficiency.

Keywords: biogas; bio-waste manure; farm setting; feeding solutions; housing; N-balance

1. Introduction

Following the concept of sustainable development as defined by the Brundtland Commission, energy systems should be ecologically, socially and economically sustainable, so that the present generation can meet its energy needs without compromising the ability of future generations to meet their energy and other needs [1]. Thereby, energy production via biomass could be regarded as a promising approach, which helps to preserve non-renewable resources, improves energy security, mitigates the greenhouse effect and promotes regional development [2–4]. According to AEBIOM (European Biomass Association) (2013) [5], bioenergy represented 68% of the total gross inland consumption of renewables in Europe in 2011. Use of renewable biomass (including energy crops and organic wastes) as an energy resource is not only "greener" with respect to most pollutants, but its use represents a closed balanced carbon cycle with respect to atmospheric carbon dioxide. A third concern is the recognized need for efficient methods for treatment and disposal of large quantities of municipal, industrial and agricultural organic wastes [6].

Abbasi and Abbasi [7,8] give a rather isolated standing about biomass used for renewable energy. In their review, the authors state that biomass appears to be a very attractive source of renewable energy, only if seen from the limited perspective of standing crop, theoretical replenishing ability and 'carbon neutral' character as a fuel. Biomass energy is indeed a sustainable option, and it has proven to be so for thousands of years, but only as long as it is used to a very limited extent. Other forms of bioenergy raise perplexity. A review of studies comparing bio-ethanol systems to conventional fuels on a life cycle basis affirm that the balance of environmental impacts of current liquid fuels from biomass is ambiguous. Apart from the definite advantage of biofuels, their impacts on acidification, human and ecological toxicity and eutrophication have been evaluated more often unfavorably than favorably [9]. Even their economic viability is still a critical issue to large-scale commercialization [10]. According to Awudu and Zhang [11], due to the nature of the biofuel supply chain, many uncertainties exist. The uncertainties include, but are not limited, to raw material supply, finished goods demand, price, pre-treatment production, yield and transportation uncertainties. In order to achieve optimal performance, the decisions of the biofuel supply-chain's management should incorporate these uncertainties. The net energy yield per hectare as the difference between the total energy gain from biofuel and biogas minus the fossil fuel input into the production process is 178 GJ (1 gigajoule = 278 kWh) in the case of biogas and, thus, more favorable in comparison to liquid fuels. Plant oil (35 GJ), sugar beet (88 GJ), grain (30 GJ) and lignocellulose (18 GJ) are less efficient with regard to the area under cultivation. Even the biomass-to-liquid (BtL) technology generating the so-called second-generation biofuels, which is not yet applicable to series production, yields just 135 GJ net energy per hectare. The BtL technique makes use of the whole plant, while first-generation biofuels only use the starchy and oleic parts of the feedstock [12,13]. These findings indicate in certain respects the environmental and economic advantageousness of biogas [14].

Biogas from Anaerobic Digestion (AD)

Over the last few decades, interest has increased in the potential for biofuel as a means of reducing dependency on fossil fuels and developing environmentally-friendly and renewable energy. Biomass includes all plant and plant-derived materials, including animal manure, not just starch, sugar and oil crops already used for food and energy [10]. The biomass resource base is composed of a wide variety of forestry and agricultural resources, industrial-process residues and municipal-solid and urban-wood residues. Biofuels produced from biomass are classified according to three generations of processing technology, while Awudu and Zhang [11] classify biofuels in four categories. According to Chynoweth *et al.* [6], biomass may be converted to a variety of energy forms, including heat (via burning), steam, electricity, hydrogen, ethanol, methanol and methane. The selection of a product for conversion is dependent upon a number of factors, including the need for direct heat or steam, conversion efficiencies, energy transport, transformation and use hardware, economies of scale and the environmental impact of conversion-process waste streams and product use. Under most circumstances, methane is an ideal fuel. Biogas is produced by anaerobic digestion or intensive fermentation of organic matter (OM). Feedstocks of this process are energy crops, but also manure, sewage sludge, municipal solid and biodegradable waste [12,15–17].

Anaerobic digestion is applied in Europe to the treatment of agricultural waste mainly in Germany, Austria, Denmark, Italy, the Netherlands and Spain [18]. Anaerobic digestion (AD) of dairy manure is an attractive treatment that provides benefits, such as pollution control, odors and pathogen level reduction, nutrient recovery and energy production [19–23]. Biogas is a combustible gas consisting of methane (CH_4, 50%–80%), carbon dioxide (CO_2, 20%–50%) and small amounts of other gases and trace elements. The digestate is the decomposed substrate, rich in macro- and micro-nutrients and therefore valued as plant fertilizer. Every biomass that is suitable to be fermented is named the "substrate". When used in a fully-engineered system, AD technology not only prevents pollution, but also allows for sustainable energy production, as well as for compost and nutrient recovery [24]. Nowadays, decentralized farm-based manure facilities represent probably the most common AD technology in low-income agricultural countries (e.g., China and India) to provide biogas for cooking and lighting [25]. Like natural gas, biogas has a wide variety of uses. Braun [20] summarized the range of biogas use options for energy production. The simplest energy application of biogas is heat production through natural gas boilers modified for raw biogas. Cleaned biogas can be inserted into municipal gas pipeline grids for cooking use [26]. Currently, biogas is mainly used for power generation through combined heat and power units with gaseous fuel engines or for feeding biogas grids [27].

If sufficiently cleaned of water, hydrogen sulfide and carbon dioxide, biogas acquires the same characteristics as natural gas and can be fed into the local gas distribution grid [12–28]. Power generation from biogas with even higher efficiency may offer fuel cell technology in the future [27]. Biogas emerges in the current scenario as the "renewable of the future", though requiring deep research and efforts to be improved and possibly integrated with other renewables. There are several issues that need to be studied and assessed more in depth [8]. Some of them are the improvement of the LCA of technologies, the development of models on energy and environmental balance, simultaneous monitoring of the critical parameters of the anaerobic digestion process, optimization of mixed substrates co-digestion and integration and innovation of pre- or post-treatment technology. The full benefits of AD have not been realized, even because of the perceived costs involved and because the system is not well known to the agricultural, industrial and engineering communities.

2. Materials and Method

Nowadays, a whole farm perspective is necessary to deal with the environmental concerns due to livestock activities. The approach has to consider the strong links among feeding, housing, treatment processes, storage conditions and field application practices along the manure management chain, because it affects soil, air and water quality, the crop growth and, consequently, farm income. The selection of livestock manure management options is becoming a strategically important task that farmers and public policy makers have to face [26]. In Europe and developed countries in general, one of the common tendencies of animal production activities is to intensify the animal production in relatively small areas, in order to reduce the production costs [29]. In those areas, the production of manure is consequently huge, and land application, the traditional dairy manure management strategy, is posing serious environmental pollution problems [30,31].

This paper presents the topic of the management of livestock effluents and, therefore, nutrients (particularly N) in the framework of biogas supply chain. The bio-refinery will be analyzed as a unique system, from the farm to the biomass produced and sent to anaerobic digestion, focusing on the fate/change of the flow of material and nutrient content through the system. Modifications might be due to feed (V1), housing type (V1), effluents amounts and storage (V2) and the presence of co-substrates (V2); those are the variables described in this paper (Vn). Farm/medium-scale biogas plants usually work in the following schematic way, as proposed by [32]. Livestock effluents (V2) eventually mixed with other agricultural residues, produced by animals bred under specific conditions (V1), are collected and sent to the digester tank (V4). Pre-treatments (V3) and post-treatments (V5) can respectively precede and follow this step, according to the composition, nutrients content, volume and fate/use of the effluents. In the reactor, in the absence of oxygen and under carefully controlled conditions, anaerobic microorganisms start the transformation and the decomposition of substrates, and anaerobic digestion takes place. The resulting biogas (V4) is collected, stored and can be transformed into heat or electric power, or it can be used directly as a gaseous fuel. Digestate, the solid rejected part coming out from the digester, is usually stored and used as a fertilizer or soil conditioner (V6). Inputs and outputs are different for each phase of the biogas supply-chain. We gave a description of inputs and outputs for V1 and V2 by arbitrarily considering four cattle farms (Table 1). For each category, we considered the most feasible solutions, in order to highlight possible/best practices for improving the system. We always gave description of inputs and outputs within each single step according to the final scope of the bio-energy refinery: to minimize environmental impacts, to maximize beneficial externalities and to optimize material-flow in order to avoid surplus/deficit of nutrients.

3. Results and Discussion

3.1. Farm Step

"Typical farm" groups have been traditionally categorized. A shrewd evaluation of the flow of material, which passes through the biogas refinery, is strongly affected by the characteristics of the livestock bred. In general, it is influenced by the setting of the stall (intensive, integrated or extensive) and, in particular, by the feed supply, housing types and effluent management and storage on the farm.

According to [33], the indirect estimation of nitrogen content (N_c) can be made according to nitrogen balance (Equation1):

$$N_c = N(effluent) = N(excreted) - N(volatilized)$$
$$N(excreted) = N(feeding) - N(animal\ products, milk, eggs, meal) \quad (1)$$
$$N(volatilized) = (0.1\ N_{feces}) \times F_s + N_{urine} \times F_l$$

where:

- N_{feces}: (the amount of feed provided by the ration (kg) × crude protein (g kg $^{-1}$ TS (total solids))) − (the amount of feed provided by the ration (kg) × digestible protein (g kg^{-1} TS))
- N_{urine}: $N_{sup} - N_{feces} - N_m - N_g$
- F_s: factor of solid nitrogen losses = $F_s = 1 - (1 - L_d/100) \times (1 - L_s/100) \times (1 - L_a/100 \times R)$
- L_d: direct losses during first days after excretion = 4% in stables with full floor drained; 9% in stables with full floor; 10% in stables with slatted floor; 10%–15% in stables with permanent litter material.
- L_s: losses from storage/processing = 1%–6%, depending on straw content; if composted, 35%.
- L_a: losses from application on crops = 80%–100% manure.
- R: factor of reduction for application types = 0.05 for injection in the soil; 0.1 if immediately plowed; 0.5–0.1 if later interred, depending on the environmental conditions and the type of soil (higher on dry, sandy soils).
- F_l: factor of liquid nitrogen losses = $F_l = 1 - (1 - L_d/100) \times (1 - L_s/100) \times (1 - L_a/100 \times R)$
- L_d: direct losses during first days after excretion = 4% in stables with full floor drained; 9% in stables with full floor; 10% in stables with slatted floor; 10%–15% in stables with permanent litter material.
- L_s: losses from storage/processing = slurry, 3%–7% in open tank; 1% in closed tank; dense slurry (feces + urine), 2%–5% in open tank; 0.7% in closed tank.
- L_a: losses from application on crops = 50%–100% slurry.
- R: factor of reduction for application types = 0.05 for injection in the soil; 0.1 if immediately plowed; 0.5–0.1 if later interred depending on the environmental conditions and the type of soil (higher on dry, sandy soils).
- N_{sup}: (amount of nitrogen in feed ration): amount of feed provided by the ration (kg) × N_{cp}.
- N_{cp}: crude protein (g kg^{-1} TS)/6.25.
- N_m: kg of milk produced.
- N_g: kg of meal produced.

A huge amount of data is necessary in order to precisely estimate the actual nitrogen content of the effluents produced at the farm. Three main aspects related to the "farm step" can be identified: (1) farm setting; (2) housing type; and (3) feeding type and breeding management. Effluents storage conditions are also essential for determining nitrogen losses after excretion. Animal manure collected in housing systems has to be stored inside or outside the stall until its application in the field. The size and nature of storage depend largely on the value of the nutrients in the manure and on the regulatory climate [34]. Often, the storage capacity is designed to allow timely spreading of the manure in the field, *i.e.*, during the growing season when the crop can utilize the plant nutrients. Loss of NH_4^+ via volatilization from animal houses, manure stores and applied manure will reduce the fertilizer value of animal fertilizers applied in the field. In addition, the variability of NH_3 emission will cause variability and uncertainty in the fertilizer efficiency of the manure, reducing farmers' confidence in manures as a source of N for crops. This fact may lead them to oversupply the crops with N, in this way leading to reduced crop quality and increased losses of nitrogen to the environment by leaching of nitrate (NO_3^-) and emission of nitrous oxide (N_2O) [34,35]. A reliable estimate of these emissions relies on a precise description of the processes involved in the transfer of NH_3 from the manure to the atmosphere. Because of its complexity, we did not address this topic. Average data are given for completeness. According to Fixen [36], almost 30% of the N excreted is lost from livestock buildings or during storage. Approximately 19% is lost via emissions of ammonia (NH_3), 7% via emissions of other N gases and 4% via leaching and run-off. A further 19% is lost via NH_3 emissions after application of the manure to land. The results show that only *ca*. 52% or less of the N excreted is potentially recycled as a plant nutrient [36]. These emissions constitute an important loss (up to 83%) of valuable N fertilizer.

3.1.1. Farm Setting

Three main divisions of farm-system exist: intensive, integrated and extensive, the latter including organic management [37]. This separation summarizes the three main approaches to nutrient management in farming. Intensive farm systems seek to maximize yield through best management practices, which involve the efficient use of all inputs, including fertilizers and plant protection chemicals, crops and crop rotations, livestock breeding programs and, often, precision agricultural techniques. Integrated farming aims at using fewer inputs, especially less fertilizer and pesticide, accepting slightly smaller yields and gross profit, while maintaining net profitability through the reduced costs of inputs. Extensive and organic systems rely on low rates of inputs to attempt to balance offtake in products. Recycling of animal manures and composted wastes is central to organic management systems. An example of "typical farm" groups, which will be used in the following paragraph, as well, is given below. The estimation of effluent amounts for each farm is the first step in the evaluation of material and nutrient management and allocation (Table 1).

Table 1. "Typical farm" groups' characteristics, in terms of animals bred, livestock size and effluents produced.

Parameters	**Animal**	**U.M.**	**Farm setting**			
Type	Dairy cattle [b]		Extensive	Extensive-integrated	Integrated-Intensive	Intensive
Size of Herd			Min	Small	Medium	Max
		No.	≤20	90	320	≥550
Daily effluents [a]		kg	≤900	4050	14,400	≥24,750
		m^3	≤1	4.5	16	≥27.5

[a] Free housing (bunk), bedding (rump to rump), straw, based on [33]; [b] no differences in terms of the cattle category are considered here.

3.1.2. Herd Composition

According to Goulding *et al.* [37], the number of replacement cows needed to ensure adequate substitution of reformed cows depends on several factors, among which the mean reproductive parameters of the herd are particularly important. This quantity is calculated by dividing the average number of parts per cow per year by the average number of parts per cow per life. The analysis assumes that calves and young heifers represent 20% of the herd, heifers 11.6% of the herd pregnant heifers 12.7% of the herd and productive cows 55% of the herd (of which, only 85% is dairy cows). The composition of herds is crucial to evaluate the biogas productive potential. The productive cows, in particular dairy cows, are those that need the greatest feeding ration and, consequently, have the most significant amount of effluents excreted (Table 2). Similarly, the amount of straw or another litter material used in the different phases is critical for the definition of biogas productive potential.

Table 2. Typical characteristics of cattle categories in terms of life weight and livestock effluents produced. Data updated and averaged on [38–41].

Animal category	**Life weight**	**Livestock effluents** [a]	
	kg	kg day^{-1}	m^3 day^{-1} [b]
Calf (0–3 months)	70	4.4	0.005
Calf (3–6 months)	140	8.6	0.009
Heifer (6–12 months)	230	20	0.022
Heifer (12–24 months)	390	34	0.037
Veal (12 months)	400	23	0.025
Dairy cow (>12 months)	500–600	50–60	0.055–0.066

[a] Livestock effluents = slurry + manure, with free housing (bunk), bedding (rump to rump), straw, based on [33]; [b] a density of 900 kg/m^3 is assumed.

A first rough estimation of the nitrogen content of the effluents produced in the farm is based on tabled average value (Table 3). Average nitrogen content is about 3.5‰ for dairy cows livestock effluents, as the average value from literature reviewed data (Table 4).

Table 3. Typical characteristics of effluents, in terms of total solids, volatile solids, total nitrogen and ammonia content. Data averaged based on [38,40–42].

Effluents	**Total solids (TS)**	**Volatile solids (VS)**	**Total nitrogen (NTK)**	**Ammonia nitrogen ($N\text{-}NH_4$)**
	%	%TS	g/kg	%NTK
Dairy cows	4–11	65–85	2.5–4.5	40–65
Pigs	2–6	40–60	2–5	70–85
Agricultural residues	5–10	65–80	3.5–7	30–65

Table 4. Typical herd composition of "typical farm" groups considered in this review, amount of livestock effluents produced according to the animal category-specific effluent production and nitrogen excretion, by using the data of Tables 1 and 2.

Farm setting	No. of animals	Calf, young heifers [a]	Heifers, veal [b]	Pregnant heifers [c]	Productive cows [d]	Livestock effluents [e]		Nitrogen content [f]
		No.	No.	No.	No.	kg day^{-1}	m^3 day^{-1}	kg day^{-1}
Extensive	20	4	2	3	11	787	0.87	2.75
Extensive-integrated	90	18	10	12	50	3257.2	3.62	11.40
Integrated-Intensive	320	64	37	41	177	11,524.6	12.81	40.34
Intensive	550	110	65	71	304	19,853	22.06	69.49

[a] The average value of 6.5 kg day^{-1} of effluent produced is considered (Table 2); [b] the average value of 27 kg day^{-1} of effluent produced is considered (Table 2); [c] a value of 34 kg day^{-1} of effluent produced is considered (Table 2); [d] the average value of 55 kg day^{-1} of effluent produced is considered (Table 2); [e] livestock effluents = slurry + manure, averaged on free housing (bunk), bedding (rump to rump), straw, based on [33]; [f] the value of 3.5 g N kg^{-1} of effluent produced is assumed (Table 3).

3.1.3. Housing

The correct evaluation of livestock effluents quantities, divided into manure and slurry, is crucial. On the one hand, it is central for the proper determination of the maximum BMP (biomethanization potential) and the consequent sizing of anaerobic digesters. BMP is the methane yield, reflecting the destruction of organic materials, according to the methane potential of each organic component in the volatile solids (VS) [43]. On the other hand, it is necessary for the precise determination of the actual amount of N_c in the effluents and, consequently, for the adequate determination of quantities spreadable over available acres. Housing types for dairy cows are classified into two major groups. Fixed housing is especially used in small herds (up to 35–40 cows). In this case, the productive cows are tied in a box, while calves and young heifers are free. Free housing is the most recently introduced type of housing, and it can be considered today a practically forced choice. This type of housing can be conducted with different configurations, which primarily differ in the presence of bunks for animal rest, in the use of straw or other litter materials and in the presence of areas with more or fewer quantities of straw. Webb *et al.* [44] found that housing systems with deep litter emit more NH_3 than tied stalls. This is due to the smaller emitting surface area in a tied stall. Different housing types affect mainly the distribution between the slurry and manure of the effluents produced. The main housing techniques and the effects that these may have on the management of effluents and on nutrient content are summarized in Table 5.

Table 5. Main housing techniques related to the amount of effluents produced (manure and slurry) and the nitrogen excreted, per main cattle category. Data are updated and averaged based on [36,38,41].

Housing					Nitrogen to field (net of losses)	
Animal	**Housing**	**Presence/Type of bedding**	**Litter material [a]**	**Life weight**	**N Slurry**	**N Manure**
				kg	kg day^{-1}	kg day^{-1}
Dairy cow	Fixed housing	Bedding	Straw	600	0.064	0.163
		No bedding	-		0.227	-
	Free housing (bunk)	Bedding (rump to rump)	Straw		0.139	0.088
		Bedding (head to head)			0.088	0.139
		No bedding	-		0.227	-
	Free housing (Litter)	Bedding removed (3 months)	Straw		0.083	0.144
		Bedding removed (30–60 days)			0.102	0.125
		Inclined bedding continuously discharged			0.064	0.163
Veal and heifer	Free housing (bunk)	Slatted floor	Straw	300	0.098	-
	Free housing (Litter)	Only in rest area (removal at end of the cycle)	Straw		0.050	0.048
		Also in feeding area (frequent removal)			0.014	0.084
		Inclined bedding continuously discharged			0.014	0.084
Calf	Free housing (Litter)	Bedding	Straw	125	0.007	0.034
		Slatted floor			0.041	-
		Single box (water cleaning)			0.024	0.017

[a] Straw is assumed as the litter material, but also sawdust can be used.

3.1.4. Feeding and Breeding Management

The best ways to reduce the amount of nutrients excreted by animals include matching the amount consumed to that needed, in order to meet the animals' requirements and to increase the efficiency of the utilization of the nutrients consumed [45]. Lazzerini *et al.* [33] underlines the poor efficiency of N conversion into product (25%–45%) and the large amounts of N in animal diets, which are converted into excreta. Methods currently used to obtain a reduction/recovery/control of the nitrogen load, related to this first step of the chain, are usually named "rational management of effluents" [46]. The N abatement techniques are based on the reduction of protein nitrogen in the diet and/or the efficiency's increase of nitrogen use. In fact, with the optimization of the protein ration, a reduction of 10% of the nitrogen excreted for each percentage point of protein reduction in the ration can be achieved. The formulation of the ration with a "safety margin" of nutrients (from 30 up to 50%) results in excretion of the excess N and P. The goal of efficient and productive feeding of animals, within economic and environmental constraints, is to provide essential available nutrients for maintenance and production while minimizing excess amounts. Formulating the protein content of cattle rations, to meet the animals' requirements for essential amino acids, can reduce N excretion by 15%, compared with more traditional feeding. It is possible to reduce N excretion up to 40%–50% by reducing the crude protein of the ration and adding supplemental amino acids. By reducing the administered nitrogen, the amount of nitrogen to the field can be reduced from 18% to 30% if compared with a standard diet [47]. A "low protein diet" can reduce the volume of slurry from 9.5% to 11.3%. Reduced dietary N input resulted in reduced CH_4 and N_2O emissions. However, in order to transfer a number of scientific findings to the operational level, proper application of precision farming technologies must be applied, particularly with regard to the strict record of the amount of feed assumed by animals [47].

Several techniques can be used in feed preparation, handling and delivery that can affect animal performance and, consequently, nutrient excretion. For instance, ensiling forages and cracking grains increases the digestibility of the ration for beef and dairy cattle. Similarly, lactating dairy cows can be fed with specific rations at separate periods in their milk production cycle. Consequently, fewer nutrients are wasted and excreted (from 5 to 10% less). This evidence requires grouping or penning animals together of similar ages, gender, weights and (or) production or management groups. Regulation and maintenance of feeders, bunks and waterers minimize the spillage of feed and water into the manure storage. Several new technologies are being developed and tested to enhance the nutrient content or utilization of feed ingredients or to alter the availability of nutrients in current commercial feeds. Within those are enzymes, genetically-modified feed ingredients and feed processing technologies to enhance the availability of nutrients to meet the needs of specific animals and reduce the excretion of nutrients. These new technologies will provide nutrients in proper balance that will allow "precision-feeding" of animals.

Table 6 summarizes the effects of different feeding types on the effluents amount and the nitrogen excreted, for each "typical farm" group. This overview should give an idea of the importance of managing the feeding step well, at different farm size levels. Farm setting and herd composition are even taken into account according to Tables 1 and 2.

Table 6. The main feeding solutions, compared with a regular diet, related to the amount of effluents produced (manure and slurry) and nitrogen excreted, per "typical farm" group. Data elaborated based on [46–48].

		Regular diet [b]			**Hypo-protein diet** [d]			**Protein content on animals' needs** [e]	**Reduced Crude protein content** [f]	**Animals categories grouped** [g]
Farm setting	**No. of animals**	**Livestock effluents** [a]		**Nitrogen content**	**Livestock effluents** [c]		**Nitrogen content**			
		kg day^{-1}	m^3 day^{-1}	kg day^{-1}	kg day^{-1}	m^3 day^{-1}	kg day^{-1}			
Extensive	20	621	0.69	3.15	557	0.62	2.40	2.68	1.73	2.96
Extensive -integrated	90	2808	3.12	14.24	2518.77	2.80	10.83	12.11	7.83	13.17

Table 6. *Cont.*

		Regular diet [b]			**Hypo-protein diet** [d]		**Protein content on animals' needs** [e]	**Reduced Crude protein content** [f]		**Animals categories grouped** [g]
Farm setting	**No. of animals**	**Livestock effluents** [a]		**Nitrogen content**	**Livestock effluents** [c]		**Nitrogen content**			
Integrated-Intensive	320	9945	11.05	50.45	8,920.66	9.91	38.34	42.88	27.75	46.66
Intensive	550	17,118	19.02	86.85	15,354.85	17.06	66	73.82	47.76	80.33

[a] Considering free housing (bunk), bedding (rump to rump), straw. The values of effluents produced are slightly lower and of nitrogen content slightly higher than the values in Table 4, since here, differences between the manure and slurry produced, according to Table 5, are considered; [b] considering a value of 3.5 g N kg^{-1} of effluent produced for a regular diet; [c] an average reduction of 11.3% of slurry excreted is assumed; [d] an average reduction of 24% of N excreted is assumed; [e] an average reduction of 15% of N excreted is assumed; [f] an average reduction of 45% of N excreted is assumed; [g] an average reduction of 7.5% of N excreted is assumed.

3.2. Biomass Step

3.2.1. Choice of Organic Matrices

Incineration or thermal gasification of biomass is the most efficient method to produce energy only if the dry matter (TS) content of the biomass is high, *i.e.*, above 40% [34]. Untreated animal manure typically has TS content much below 40%, as shown in Table 3. Therefore, the alternative anaerobic digestion process is a very good option, as a wet biomass is perfectly suited for the anaerobic biogas process [34]. Bio-waste contains a high amount of only partially-oxidized organic components. By fully oxidizing these components, the stored energy might be released and used [34].

According to Raju [49], the substrate used to produce biogas in a digester is an important aspect that determines the organic loading rate (OLR) (kg VS m^{-3} day^{-1}), the amount of biogas (m^3 ton^{-1} fresh substrate) and the final BMP (m^3 CH_4 kg^{-1} VS). Biogas yields (m^3 ton^{-1} VS) for categories of substrates suitable for on-farm AD vary from 200 to 550 for livestock effluents, from 550 to 750 for biomass from dedicated crops, from 350 to 500 for agricultural residues and from 400 to 800 for agro-industrial and food production residues. If slaughterhouse bio-waste is added, from 600 to 950 m^3 ton^{-1} VS of biogas can be obtained. Sewage sludge and the organic fraction of urban waste provide from 250 to 350 and from 400 to 600 m^3 ton^{-1} VS of biogas [38].

The advantage of AD is that almost any biomass can be used as a substrate for biogas production [50]. This variety of substrates can be used as a mono-substrate or as mixed-substrates in co-digestion processes. Much research has gone into identifying species and cultivars of energy crops that can produce more biogas. However, energy crop production has been criticized for competing with food production for arable land [49]. Agricultural and livestock residues offer an excellent alternative to energy crops. The addition of agro-industrial or readily degradable waste from food processing is needed to give a sustainable energy production. Animal slurry has low organic matter content and about 30% of it is slowly degradable [34]. Agricultural residues, such as straw, rice husk or wood chips, often contain high concentrations of ligno-cellulose, which is difficult to degrade.

Animal manure contains more readily degradable organic materials, such as proteins and lipids, than other agricultural by-products, but it also has a high content of lignocellulose bio-fibers [43] (40%–50% of the total solids [51,52]), a considerable part of which are recalcitrant to anaerobic digestion. The use of such biomass for AD may require pre-treatment to improve their degradability. Moreover, animal manure has very variable characteristics, not only between animals (*i.e.*, pigs, cattle and poultry), but also within the same animal categories between countries and farms [53,54]. Those differences depend mainly on the farm production, on the animal feed composition and on the water consumption. Seasonal fluctuations can also be observed within the same farm.

Meadow grasses are a promising source of biomass [55] and a good option for AD, due to various reasons, such as availability, the possibility for nutrient transfer and low energy and chemical input requirements. Co-digestion of manure and biomass increases the methane yield when compared to digesting solely manure, but the results are sensitive to many operating parameters, not only related to the reactor type, but also the type of manure and biomass and the ripeness of the biomass [56].

Bringing biofuel production to the farm-scale provides an opportunity for the agricultural sector to reduce its reliance on imported fossil fuels, while improving the soil, water and air quality [57]. In effect, livestock/agricultural waste-to-bioenergy treatments have the potential to convert the treatment of livestock waste from a liability or cost component into a profit center that can: (1) generate annual revenues; (2) moderate the impacts of commodity prices; and (3) diversify farm income [58]. However, biogas production needs to be cost-effective, and excessive costs may provide an argument to (temporarily) loosen goals for a certain areas [59]. The analysis of costs and benefits associated with residual waste treatment options is a subject that has been discussed in a range of studies. Of course, different treatments will fare slightly better or worse depending on the composition of the material being treated [60]. The choice of organic matrices to be used in the process of AD is conducted following different management logics (Table 7).

(1) The choice of giving priority to farm effluents or waste: In recent times, this aspect has been associated with the logic of efficiency improvement of AD and, thus, to the agro-energy profitability increase of the farm.
(2) The ability to find dedicated biomass: It is usually easy to find dedicated biomass grown on the land of the same farm running the biogas plant. However, agreements for the provision of dedicated biomass from nearby farms are also common.
(3) The ability to find suitable products at low cost: Many experiences can be cited for use of by-products and waste present in large quantities near the biogas plant, often with little or no cost at all, with the exception of transportation costs. Therefore, the possibility to reduce the cost of biogas production makes this solution appealing, even if it must be accompanied by a careful combination of organic matrices.
(4) The cost of the organic matrix used: any choice of matrices for the process of AD must be assessed in relation to its value (€ ton^{-1} of substrate). For instance, many effluents, while presenting zero cost, have very low biogas-yields and/or induce difficulties in the process or the supply-chain.
(5) The productivity in terms of biogas (m^3 kg^{-1} VS) of the matrices available: the biogas-yield obviously depends on the type of matrix. To estimate the unit cost of biogas producible (€ m^{-3} of biogas), it is necessary to consider the matrices as a function of this aspect.

Table 7. The matrix summarizes biomass options and logics for choosing the substrate for the AD process.

	Variable input	Description of input
Substrate	Livestock effluent Biomass from dedicated crops Sewage sludge Organic fraction of urban waste Agricultural residues Agro-industrial and food production residues	Choice of organic matrices to be used in the process of AD (both as mono-substrate or in co-digestion)
Depending on:	Choice of giving priority to farm effluents or waste Ability to find dedicated biomass Ability to find suitable products at low cost Cost of the organic matrix used Productivity in terms of biogas	Factors affecting choices, based on specific management logics

According to [58], manure processing by anaerobic digestion and converting the biogas into electricity with a combined heat and power (CHP) engine show negative costs, *i.e.*, economic benefits. Investment is recovered by electricity sales, savings on heating and "green power" and CHP support. However, costs are only negative if support schemes continue to exist and if digestate can be used as fertilizer for croplands without further treatments. A precise cost-benefit analysis (CBA) should combine mass flow data with unit cost factors in order to calculate the environmental and financial costs for each scenario. Capital investment, operational costs for process feedstock, greenhouse gases (GHGs) and air quality externalities, power supply, logistics and fertilizer costs are important factors in performing CBA. The definition of the investment costs' reference standard is complicated. In general, for most of the plants, a range between 250 and 700 € per cubic meter of anaerobic digester can be defined, or 2500–7500 € per kW of electricity installed in CHP. The threshold for making a profitable biogas plant is usually about 50–100 kWe of installed power.

In selecting options for biogas use, some important aspects must be taken into account. The main form of energy consumed by the farm: it is important to consider the type of user, consumption trends (mechanical energy for stationary or mobile applications, cooling energy, low-temperature thermal energy, steam) and the energy sources used. This assessment may lead to solutions of biogas use other than electricity generation. Consumption trend during the year: biogas production, if well planned, is constant throughout the year, while energy consumption frequently has an irregular trend or is characterized by periodicity. Efficient use of biogas should be oriented to serve users continually as much as possible, in order to minimize expensive fuel storage. Exploitation of biomethane as fuel: the European Directive 2003/55 authorizes the placing of other types of gas in natural gas networks. For bio-methane production, water, sulfur compounds, halogenated molecules, carbon dioxide, oxygen and metals must be eliminated.

Considering that 23 MJ m^{-3} biogas (65% methane), 11.5 MJth (thermal energy) and 8.74 MJe (electricity) from a CHP engine can be obtained or with 1 N m^3 biogas, it is possible to produce, on average, 1.5–2 kWh of electricity and 2–3 kWh of thermal energy [38]. According to these values and considering that average biogas yields for cattle effluents range from 200 to 400 m^3 ton^{-1} VS, extensive farms can convert 42 m^3 day^{-1} of biogas in about 4 kWe, while intensive farms will obtain 1155 m^3 day^{-1}

of biogas and up to 93.5 kWe. In integrated farms, according to more extensive or intensive settings, values from 320 to 672 m^3 day^{-1} of biogas can be produced, obtaining average values from 15.3 to 54.4 kWe.

3.2.2. Characteristics of Livestock Effluents Compared to Other Substrates

Above the other factors, the productivity of biogas in terms of BMP (m^3 CH_4 kg^{-1} VS) of different substrates is crucial. BMP is the most important parameter to assess the quality of feedstock among other biological and physiochemical parameters in AD. It is used to design real scale biogas digesters. It can be used for kinetic modelling to predict biogas yield, and it has furthermore been used as the most relevant indicator for assessing digestibility [34]. Table 8 presents BMP and TBMP (theoretical BMP) values for different substrates, in order to compare the biogas production from various biomasses used in the AD process. TBMP is a stoichiometric approach, which assumes that all VS can be converted to methane. Anaerobic digestibility (BMP × $TBMP^{-1}$ × 100) depends on the physical resistance of each biomass's component (*i.e.*, lignin, lipids, protein) of VS against hydrolysis. TBMP is a useful tool for assessing the energy potentials of biomass having a larger fraction of readily degradable VS that can typically be found in non-waste biomass and energy crops not containing lignocelluloses. For these biomasses, the measured BMP is close to TBMP. However, most of the waste-biomass, such as animal slurry, present critical digestibility below 50% of TBMP, and many plant biomasses have a low digestibility due to lignocellulose [43–53].

Table 9 summarizes the substrates usable/available for each "typical farm" group, based on management logics, according to the considerations given in this paragraph. In particular, the pros and cons of the use of livestock effluents in the AD process are summarized in Table 10.

Table 8. Biomethanization potential (BMP) (CH_4NL kg^{-1} VS), theoretical BMP (TBMP) (CH_4NL kg^{-1} VS) and the digestibility of different biomass [43–53].

Biomass	**BMP**	**TBMP**	**BMP/TBMP × 100**
	CH_4NL kg^{-1} VS	**CH_4NL kg^{-1} VS**	-
Piglet manure	417	449	92.9
Sow manure	213	537	39.7
Pig fattener manure	345	527	65.5
Deep litter manure	237	442	53.6
Cattle manure	223	523	42.6
Maize (corn)	478	501	95.3
Maize (leaves)	402	445	90.4
Lawns + clover	328	484	67.6
Lawns	339	505	67.1
Wheat straw	227	477	47.6
Tufted hair-grass	235	458	51.3
Ivy	231	486	47.5
Willow	164	513	32
Birch tree (branch + leaves)	240	546	44
Common reed	188	486	38.6

Table 9. Biomasses available/feasible for AD for each "typical farm" group.

Parameters	**Animal**	**U.M.**	**Farm setting**			
Type	Dairy Cattle [a]		Extensive	Extensive-integrated	Integrated-Intensive	Intensive
Size of Herd		No.	Min ≤20	Small 90	Medium 320	Max ≥550
Daily effluents [b]		Kg	≤621	2808	9945	≥17,118
		m^3	≤0.69	3.12	11.05	≥19.02
Other biomasses for AD	Biomass from dedicated crops	feasible/available	No	No	Yes	Yes
	Sewage sludge		No	No	Only if locally produced	Yes
	Organic fraction of urban waste		Only on farm produced	Only if locally produced	Yes	Yes
	Agricultural residues		Yes	Yes	Yes	Yes
	Agro-industrial and food production residues		No	Only if locally produced	Yes	Yes

[a] The cattle categories are considered in the general definition "dairy cattle", as described in Table 3; [b] the amount of effluents produced per day is based on the assumptions made in Table 6.

Table 10. Pros and cons of livestock effluents used in the AD process.

Livestock effluents: pros and cons related to their use in the AD process	
PROS	**CONS**
Very low or null matrix costs	Low methane yields
Availability in neighboring areas	Reduction of carbonaceous components contribution to soil
Valorization of waste and potential integration of income for livestock farm	Possible formation of floating crusting waste with high TS% manure types
Presence of pre-existing storage facilities	
Creation of potential easier outlets for the digestate, when spreading is expected in non-farm soils	
Stabilization of effluents with odorous emissions reduction	
Possibility to use different matrixes in the processes of co-digestion	

The main characteristics of manure that have to be taken into account are the volume and chemical characteristics. The determination of volume is required for the purposes of re-sizing the storage capacity, to correctly set the fertilization plans, to check if the volumes of effluents produced differ from those calculated indirectly and for the size of the effluent treatment plants. The determination of chemical characteristics is necessary for the purposes of their correct use for crop fertilization and the identification and design of the treatment techniques and size.

Angelidaki *et al.* [50] reviewed useful values for cattle manure characteristics. Typically, 60%–85% of the total N present in the effluent is in organic form. Most of this organic N is from the fecal material (N_{feces}). The urine contributes some organic compounds; 60%–90% of the total N in urine (N_{urine}) is urea, which is rapidly hydrolysed to ammonium-N. Boe *et al.* [52] found a mean nutrient content in cattle slurry from dairy cows of 1120 mg (NH_4-N) L^{-1} and 1380 mg (P_2O_5) L^{-1}, while Lübken *et al.* [61] found 3090 mg (NH_4-N) L^{-1} and 74,500 mg (COD) L^{-1} (chemical oxygen demand).

The composition of the material affects the rate of degradation (degradability), having decreasing values respectively for proteins, lipids, cellulose and, lignin. Cattle effluents have a greater content of cellulosic material: their degradation rate will be lower, for instance, than the one of pig slurry, which is richer in lipids. The presence of toxic elements for microbial metabolism is also an important factor. Within these are often micronutrients, such as sodium (Na), potassium (K), calcium (Ca), magnesium (Mg), ammonium (NH_4^+) and sulfur (S), which, if present in excess, can induce the inhibition of the process. Heavy metals, such as copper (Cu), chromium (Cr), nickel (Ni), zinc (Zn) and lead (Pb), if present in concentrations greater than 1 mg L^{-1}, can lead to severe damage, both to human metabolism and crops.

Anaerobic digestion of animal manure can be inhibited by ammonia (NH_3) and hydrogen sulfide (H_2S). The former is generated by the fermentation of organic nitrogen (urea and proteins) and the latter by sulfate reduction. Because of high nitrogen concentration in the manure and quite high pH values, free ammonia (FA) is considered as the main inhibitor, even if the inhibition thresholds are very dependent on the inoculum and its adaptation to the inhibitor [62]. However, FA concentrations above 1500 mg N L^{-1} are not desirable. This fact highlights the importance of balancing the N content of manure while maintaining a proper C/N ratio. It is necessary to maintain the adequate composition of the feedstock for efficient plant operation, so that the C/N ratio in the feed remains within the desired range. During anaerobic digestion, microorganisms utilize carbon 25–30 times faster than nitrogen. Thus, to meet this requirement, microbes need a 20–30:1 ratio of C to N with the largest percentage of the carbon being readily degradable [63].

Cattle manure presents 10–30 as the C/N ratio [34], but in the case of co-substrate added to AD, the real ratio has to be defined by summing the C/N(Xn) multiplied by the weight of each material Xn and dividing the sum by the total weight of feedstock.

Some recommendations can be extrapolated from the excursus on farm and livestock effluent biomass characteristics. Livestock activities should better integrate other agricultural and agri-food activities, in order to re-cycle both inputs and outputs. Animal production increase should no longer be stressed by genetic improvement of animals nor a strong increase of the "average daily gain". The human and economic pressure on cereals will compete more and more with livestock production. Cereals used for animal feeding should be replaced by co- or by-products from agri-food activities, allowing a reduction of the cost of animal feeding and the development of recycling systems of so far unused products. In particular, specific hypo-protein diets and housing modalities that allow a lower nitrogen content excretion and more valuable livestock-biomass should be integrated with the farm, particularly for larger ones.

4. Conclusions

Effluent management methods that are more feasible and available at different levels have to be integrated into the animal husbandry sector, in order to protect the environment and to allow one to switch back to a recycling view of manure handling. The ideal situation would be to work at the same time on both inputs and outputs of livestock production and its integration in its "regional" or geographical aspects. However, to reach such a goal, all treatment aspects have to be considered, not only the constraints, whatever they are (environmental, sanitary), but also the overall consequences, integrating economical parameters, like the cost of livestock buildings, evolution and depletion of fuel energy, phosphorus and, maybe, cheap cereals. Possible stronger policies on environmental protection have to be integrated, such as the necessity to include new "emerging" pollutant-like antibiotics, endocrine disrupters and antibiotic-resistant pathogens. The development of such new systems will require the development of new measuring devices and global methods to assess the viability of the production chain and food supply. Evidently, this raises the awareness that for each farm, solutions have to be evaluated, actively considering the features and the inherent vulnerability of the territory on which the effluents are disposed. Intensive farms are expected to be able to apply and integrate in the livestock activities and facilities the best available techniques, through which the nutrient amount contained in the effluents can be significantly reduced up to 70%. In fact, the cost of the most sophisticated and efficient treatments cannot be supported by small farms. However, extensive and/or organic farms usually better integrate livestock activities and cultivation activities. Integrated farms may present characteristics more close to extensive farms or to intensive ones. They represent a "typical farm" group, which is more easily expected to calibrate and adapt different treatment and management solutions, balancing farm-production profit, energy self-sufficiency, environmental protection and animal husbandry well-being.

Author Contributions

All authors contributed extensively to the work presented in this article. Francesca Nardin wrote the paper with input from Fabrizio Mazzetto, discussing the results, implications and commenting on the manuscript at all stages.

Conflicts of Interest

The authors declare no conflict of interest.

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