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ENVIRONMENTAL BENEFITS OF THE ANAEROBIC DIGESTION OF AGROINDUSTRIAL WASTES

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Abstract — Agrifood industry plays a relevant role in the economic development of the Autonomous Community of Extremadura (Spain), and generates vast volumes of wastes featured by both high polluting potential and moisture content. The present work reports on a detailed analysis of biogas generation (as well as of the relative methane and carbon dioxide production per ton waste) from the anaerobic digestion of industrial tomato residues and slaughterhouse wastes. For such purpose, the annual waste generation rates in Extremadura were taken as input data; the methane and carbon dioxide volumes per ton waste were assumed as those of the hypothetical case of wastes being naturally decomposed; and the obtained biogas was regarded to serve as fuel for useful energy production (heat and/or electricity). Under these assumptions, the environmental benefit of the anaerobic digestion of the wastes was quantified and compared with the greenhouse emissions that might be observed if such wastes were directly dumped to the environment.

Keywords — Agrifood wastes, anaerobic digestion, greenhouse gases

1 INTRODUCTION

The temperature of the atmosphere is balanced by the influence of a series of physical parameters: the rate of solar radiation reaching the surface of the Earth, the reflection index (albedo) of the various types of planet surface (land, sea and even clouds) and the rate of energy reradiated to the outer space [1]. The incoming solar radiation and the outgoing terrestrial radiation rates need to be balanced for the annual mean temperature of the Earth to be maintained at an approximately constant value. Therefore, any perturbation on the incoming solar radiation or on the reradiated energy from the Earth (or even on the energy redistribution within the atmosphere, or amongst atmosphere, land and ocean) might affect climate, with relevant implications on the global water hydrologic cycle and on the atmosphere and ocean circulation, which might definitively alter the weather patterns as well as temperatures and rainfall rates at regional scale [2].

Greenhouse gases (GHGs) like water vapour, carbon dioxide, methane, tropospheric ozone and nitrous oxide are transparent to shortwave solar radiation. However, the thermal energy reradiated from the Earth lies in the spectral range of long wavelength, and is therefore partially blocked by GHGs. This way, part of such thermal energy flux is retained by the atmosphere [1].

An increase in GHG concentration results in a reduction of efficiency of the planet surface as source of outgoing terrestrial radiation, and the greenhouse effect is hence favoured. As a result, a natural atmospheric effect that has occurred for billions of years due to the presence of GHGs generated in natural processes is significantly strengthened.

The amount of radiative forcing (change in the net radiative energy flux towards the surface of the Earth, expressed in W/m^2) depends on the size of the increase of concentration of each GHG, the radiative properties of the gases involved, the concentrations of other GHGs already present in the atmosphere and the residence time after emission of such elements to the atmosphere [2]. The main features of GHGs are shown in Table 1.

Concentrations of GHGs remained approximately constant during the millennium prior to the Industrial Era. However, they have shown an increasing trend due to the direct or indirect influence of human activities.

Methane concentrations in the atmosphere have suffered a 150% increase (1 060 ppmm) since 1750. The current CH_4 concentration has not been exceeded for the last 420 000 years. Methane is a GHG that emanates from both natural (wetlands) and human-induced sources, like mining industry, fossil fuels combustion, animal husbandry (plants eaten by cattle are fermented in their stomachs and exhaled methane is therefore present in manure), rice cultivation (flooded paddies produce methane as

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Table 1. Features of main GHGs (adapted from reference [2]).

	CO_2	CH_4	N_2O	CFC-11	HFC-23	CF_4
Preindustrial concentration	Approx. 280 ppm	Approx. 700 ppmm	Approx. 270 ppmm	Zero	Zero	40 ppb
Concentration by 1998	365 ppm	1 745 ppmm	314 ppmm	268 ppb[e]	14 ppb	80 ppb
Rate of change in concentration [b]	1.5 ppm/year[a]	7.0 ppmm/year[a]	0.8 ppmm/year	-1.4 ppb/year	0.55 ppb/year	1 ppb/year
Lifetime in atmosphere	5 to 200 years[c]	12 years[d]	114 years[d]	45 years	260 years	>50 000 years

a. Rate ranging from 0.9 ppm/year to 2.8 ppm/year for CO_2, and from 0 to 13 ppmm/year for CH_4 in the period 1990-1999.

b. Rate calculated for period 1990-1999.

c. A single lifetime cannot be defined for CO_2, provided the existence of different values of the absorption index for the various removal processes.

d. Lifetime defined as "adjustment period" accounting for the indirect influence of the gas on its own residence time.

e. "Billion" in "ppb" considered as 10^{12}.

organic matter decomposes in lack of oxygen) and landfills where organic wastes are broken down under anoxic conditions. Just over half of current CH_4 emissions are regarded as anthropogenic.

Systematic and representative measurements regarding the global stage of methane concentration in the atmosphere have been carried out since 1983. Moreover, the analysis of air samples extracted from ice cores and firn layers allowed the expansion of data records of CH_4 concentration to earlier dates. The current direct radiative forcing of this GHG is reported as 0.48 W/m^2, which represents 20% of all GHGs. Methane concentration in the atmosphere is still observed to be increasing, from about 1 610 ppmm by 1983 up to 1 745 ppmm by 1998, although the annual increase has declined during the same period. This rising trend showed significant variations during the nineties, was negligible in 1992 and rose to 13 ppmm by 1998. Nevertheless, there is no clear quantitative explanation for such fluctuations.

Methane is regarded as the second most relevant driver of greenhouse effect after water vapor. Provided that its lifetime in the atmosphere is much shorter than that of carbon dioxide, and also that the former is 23 times more effective to absorb terrestrial radiation, a reduction in emissions would result in rapid and significant consequences, as reported by the Clean Air Task Force, the Climate Policy Center-Europe and the Clean Air-Cool Planet

Given the adverse effects associated to the anthropogenic emission of methane to the atmosphere, efforts should be focused on the development of specific technologies to carry out controlled degradation processes of the wastes causing such emissions, so that they are not released to the environment. Such is the case of anaerobic digestion (AD).

Anaerobic digestion or biodigestion is a biological degradation process by which organic matter is broken down into a gaseous product called biogas and a digested effluent (a mixture of mineral elements like N, P, K, Ca and certain compounds of difficult degradation), due to the action of specific sets of bacteria (hydrolytic, acidogenic, acetogenic and methanogenic). This odor-free sludge is rich in nutrients and suitable to be used as organic amendment.

Biogas is a mixture of methane (about 50-75%, depending on the digested substrate), carbon dioxide (25-50% approximately) and some other gases like carbon monoxide, hydrogen and hydrogen sulphide present in concentration traces. Its heating value depends directly on the volumetric content of methane. This way, the heating value of a biogas containing 60% CH_4 by volume would be 60% of that of methane, i.e. about 5 500 kcal/Nm^3 (6.4 kWh/Nm^3). Biogas is therefore likely to serve as fuel for engines, turbines and boilers, either alone or mixed with other fuels.

The controlled process of AD is one of the most suitable to reduce GHG emissions, to promote energy use of wet organic wastes, as well as to enhance the use of the processed products as fertilizers [3]. This has been widely reported in the scientific literature by numerous studies on the anaerobic digestion of diverse organic wastes like cassava pulp mixed with pig manure [4], onion juice with wastewater sludge [5], tomato processing wastes [6] or slaughterhouse residues [7].

Estimates of methane emissions by usual treatment of diverse organic wastes have been reported elsewhere, like for instance in studies on manure management systems [8], storage of solids separated from pig slurry [9] and cattle grazing [10]. Many other studies have focused on the effect of AD on mitigating methane emissions to the atmosphere by considering wastes from dairy and pig farms [11], as well as cattle slurry [12].

However, the effects on mitigating methane emissions to the atmosphere by an appropriate management of wastes from agrifood industry have not been sufficiently analyzed yet. The present work reports on a review of the environmental benefits of the anaerobic digestion of wastes from tomato processing plants and meat industry. In particular, the reduction of the consequences on the greenhouse effect that might be achieved by controlled biomethanisation of the abovementioned wastes, as compared with that of the case of free release of GHGs (mainly methane and carbon dioxide) generated by uncontrolled natural putrefaction, is quantified.

The completion of such studies is definitively of special interest in certain European Regions regarded as environmental reserves (as for instance in the case of Extremadura, Spain), for which the agrifood sector has become a crucial hub for economic development. These efforts, in short, are devoted to sensitize policy makers and citizens at large about the relevance of an appropriate management of organic wastes, aimed at both significantly reducing GHGs emissions and generating renewable energy (biogas).

2 MATERIALS AND METHODS

2.1 Inventory of wastes generated by agrifood industries

Agrifood industry plays a relevant role in the economic development of the Autonomous Community of Extremadura (Spain). Unfortunately, it generates vast volumes of wastes featured by both high polluting potential and moisture content. The total amount of residues generated by agrifood industries are estimated by taking as reference the amount of raw material corresponding to a standard year. In the present work, such data were taken from the Spanish Ministry of Environment and Rural and Marine Affairs [13].

A total of 4 603 900 t tomato were cultivated in Spain by 2009, of which 1 901 600 t were cultivated in Extremadura (41.3% of national production), and 2 506 600 t were processed into other products. This allows to state that only 54.4% of tomato production is used in tomato processing plants. On the other hand, in the particular case of Extremadura, 1 875 000 t out of 1 901 600 t were processed in tomato canning plants by 2009, which means 98.6% of total regional production [13].

Two main types of solid residues are generated by the tomato processing industry: sludge from depuration of waste water (approximately 1.6% of input raw material) and wastes from peels and seeds (4% of input raw material). This way, 0.04 t peels and seeds and 0.016 t sludge are generated by each ton of processed tomato [14]. Therefore, 75 000 t peels and seeds and 30 000 t sludge were generated in Extremadura by 2009, which makes a total of 105 000 t of solid wastes generated by tomato processing plants.

On another note, Extremadura is widely known – both nationwide and worldwide- as the main producer of products from the Iberian pig, a local breed whose meat has reached high standards of quality and taste. 691 078 pigs –most of which Iberian- were slaughtered in this region by 2009, which makes 1.7% of 40 117 902 heads of cattle slaughtered in Spain during that year [15].

The meat industry generates a huge amount of solid (stomachs, fat, viscera and intestines) and liquid (blood and waste water) wastes with a strong pollutant potential.

The sacrifice of a pig is estimated to produce an amount of blood equivalent to 1.5% of its weight [16]. In order to predict the volumes of other types of wastes generated by slaughtering activities, the following data from an Iberian pig slaughterhouse located in Llerena (Badajoz) were considered in the present work. 36 093 pigs (5 573 t live weight) were slaughtered in 2009. 4 456 t meat were produced and 12 427 m^3 water were consumed. This allowed to approximately set 154.4 kg as the average weight of an Iberian pig, and 28.6 kg and 344 l water the weight of generated solid wastes and the volume of water consumed per head of cattle, respectively.

The abovementioned data give a total of 1 601 m^3 blood, 19 786 t solid wastes and 237 731 m^3 waste water from the 691 078 pigs slaughtered in Extremadura by 2009, which leads to a final volume of 259 118 m^3 solid and liquid wastes.

2.2 Anaerobic Digestion of wastes from agrifood industries

Experimental measurements on anaerobic digestion processes with 2 l and 6 l volume laboratory-scaled digesters in semi-continuous mode and continuous regime, respectively, have been performed in order to quantify the methane emissions that would be released to the atmosphere if the abovementioned residues were dumped to the environment or were taken to landfills for putrefaction.

2.2.1 Startup of the anaerobic digestion process

Wastes from slaughtering activities and from tomato processing plants lack of suitable microorganisms to activate a biodigestion process. For such reason, an acclimated inoculum ought to be necessary. The sludge used as inoculum to activate biodigestion was taken from an anaerobic reactor located at the Wastewater Treatment Plant in Badajoz. It showed optimum physicochemical features to activate the anaerobic digestion of the wastes: (i) pH close to 8, the most suitable value for the growth of methanogenic bacteria. (ii) A high value of Chemical Oxygen Demand (COD). (iii) High alkalinity and low concentration of volatile fatty acids, which ensures a strong buffering character.

Once the sludge was introduced into the digesters, they were sealed and subjected to gentle agitation so that the microorganisms come in contact with the substrate. Increasing amounts of substrate to be degraded (either slaughterhouse wastes or residues from tomato processing plants) were periodically added to the initial sludge, to that the biodigestion bacteria can acclimatize to the substrate.

2.2.2 Preparation of substrates

Once the startup of the process has been described, the procedure followed for the preparation of each of the substrates used in the anaerobic digestion experiments is explained in detail along the present subsection. Initial residues were firstly forced to undergo a mechanical treatment to reduce particle size, provided that this feature is reported in the scientific literature as one of the most relevant parameters in AD processes [17]. The lower the particle size, the higher the efficiency of the process, given the fact that a decrease in particle size implies an increase of the surface on which bacteria might act. The actual ratios of waste generation in real operating conditions at a standard industrial plant were taken into account, so that the final results might be used for future real-scaled projects.

Wastes from tomato industry (peels and seeds, as well as sludge from depuration of generated wastewater) were taken from a tomato processing plant located in the outskirts of Badajoz, and stored at -4°C to prevent degradation. The ratio these types of residue meet is reported as 2.5 kg peels and seeds per kilogram sludge. The substrate to feed the reactor was prepared according to such ratio by adding water to moisture content suitable for an appropriate AD process, i.e. 90% sewage and 10% solids (of which 7.14% corresponded to peels and seeds and the remaining 2.86% to sludge).

After adding a small volume of water to the solid wastes, they were crushed with a comminutor and a blender until particle size was reduced as much as possible. Once the solid residue was homogenized, it was mixed with water according to the abovementioned ratios.

Table 2. Physicochemical characterization of the wastes from tomato industry.

NOTE: Chemical Oxygen Demand (COD_{total}), Biological Oxygen Demand per 5 days (BOD_5), Volatile Suspended Solids (VSS), Volatile Dissolved Solids (VDS), Volatile Fatty Acids (VFA).

Parameter	Unit	Value
pH		4.55
COD_{total}	mg O_2/l	22 320
BOD_5	mg O_2/l	6 750
VSS	g/l	11.36
VDS	g/l	2.34
VFA	gCH_3COOH/l	0.33
Alkalinity	$gCaCO_3/l$	0.1
Total nitrogen	g/l	0.7
Total organic carbon	g/l	11.4
Ratio C/N		16.28

Wastes from meat industry were taken from an Iberian pig slaughterhouse located in Llerena (Badajoz). Blood and sewage samples, as well as pieces of organs, were periodically collected in 5 l cans and in sealed bags, respectively. Viscera were chopped and stored in smaller bags in the laboratory according to the appropriate proportions, which were determined so that mixture of solid wastes at laboratory was a scaled reproduction of that of output solid wastes at the slaughterhouse. As already noted, all residue samples were stored at -4°C to prevent degradation. Afterwards, the solid fraction was homogeneously crushed using a comminutor until particle size was reduced as much as possible, and then mixed with the liquid effluents according to the actual ratio met by the slaughtering activity in real-scale, i.e. 6% solid waste, 93% sewage and 1% blood.

Table 3. Physicochemical characterization of the wastes from Iberian pig slaughterhouse.

Parameter	Unit	Value
pH		6.22
COD_{total}	mg O_2/l	45 867
BOD_5	mg O_2/l	37 360
VSS	g/l	6.08
VDS	g/l	5.94
VFA	gCH_3COOH/l	1.33
Alkalinity	$gCaCO_3/l$	1.7
Total nitrogen	g/l	1.6
Total organic carbon	g/l	7.55
Ratio C/N		4.72

The slaughterhouse waste has a higher pH value (close to neutral) than that of the tomato industry residue. This feature, together with its high alkalinity, leads to a suitable buffering capacity in the reaction medium. The COD exceeded 42 g/l, which characterizes the high polluting potential of the residue, hence enforcing its suitability to undergo an anaerobic digestion process.

It should be finally noted that the carbon/nitrogen ratio is far below the optimum value recommended in the scientific literature [18].

The pH value of tomato residue, however, is quite low (below 5), which at first could impede the appropriate development of the anaerobic digestion process due to possible acidification of the bioreaction. It is well known that anaerobic degradation is set as optimal at pH close to neutral, i.e. ranging from 6.5 to 8.

Another relevant parameter is the polluting potential of the tomato residue mix, which exceeds 22 g COD per liter. The volatile acidity is not too high (0.33 g/l), although the extremely low value of alkalinity, 0.1 g/l (even below the value of volatile acidity), is very significant. This gives a hint on the acidity of the substrate and its poor buffering capacity.

2.2.3 Experimental setup

Slaughterhouse wastes were degraded in a continuous digester, which was progressively fed (dropwise along the whole day) by a peristaltic pump. The device is designed to simultaneously extract the same volume of substrate while the feeding process is taking place.

The reactor was a CSTR type (Continuous-flow stirred-tank reactor), i.e. a perfect-mixing continuous reactor with about 6 l operating volume. The reactor was controlled by an automaton which regulates the substrate feeding supply, the operating temperature as well as the agitation stage inside the reactor.

Experiments were conducted within the mesophilic range of temperature, particularly at 38°C, and such temperature was maintained via ceramic heating elements installed in the lower part of the digester.

As abovementioned, the biodigester was fed using a peristaltic dosing pump that sucks the substrate from a glass container equipped with a magnetic stirrer to guarantee homogeneity of the substrate before being introduced into the digester. The reactor content was agitated by the recirculation of part of the biogas produced by another peristaltic pump.

The biogas generated during the process was collected in a gasometer, which consists of a primary cylinder filled with water up to a certain level containing a secondary floating lower-diameter cylinder closed at its top. The gas produced inside the digester was channeled by rubber pipes towards the primary cylinder, so that the submerged secondary cylinder was pushed upwards to store the biogas inside. The volume of generated biogas could then be calculated at atmospheric pressure and room temperature from the diameter of the inner cylinder and the ascended height. Therefore, this gasometer not only provided direct visual readout of the accumulated volume of biogas, but it also guaranteed safe storage, hence preventing fire hazard, bad odor, etc.

The volume of biomass inside the digester was controlled by an overflow spillway, so that the digested effluent was collected via a cone separator. Sampling in the digester was carried out by valves installed in its lower part. Fig. 1 shows a basic scheme of the described perfect-mixing continuous reactor.

Residues from tomato industry were degraded in a digester designed to operate in semicontinuous mode. This means that a given volume of substrate was introduced into the digester once a day using a syringe, and at the same time the same volume of digested sludge was removed so that the net volume inside the reactor remained constant.

A scheme of the experimental setup used for the anaerobic digestion experiments undergone in semicontinuous mode is shown in Fig. 2.

It basically consists of a 2 l capacity glass flask, whose rim is assembled to a central tube immersed in the reaction medium, and which has an input hole to introduce the substrate and an output one to collect the biogas generated in the process.

The digestion unit was submerged in a water tank maintained at 38°C by a thermostat equipped with a heating resistor. The substrate inside the reactor was homogenized by a magnetic stirrer. It should be noted that the design of the experimental setup guaranteed a uniform temperature throughout its whole volume due to the immersion in a thermal tank and the continuous agitation of the substrate. The operating conditions should therefore be regarded as optimal.

A 5 l tank assembled to the biodigester was used to determine the volume of methane generated during the AD process. A squeeze bottle containing a sodium hydroxide solution 20% by weight was placed between the digester and the gas tank, aimed at retaining the carbon dioxide generated during the digestion process.

The methane generated during the experiment displaced water in the tank, which was collected in a measuring cylinder. This way, the volume of displaced water allowed the calculation of the volume of methane generated in each experiment.

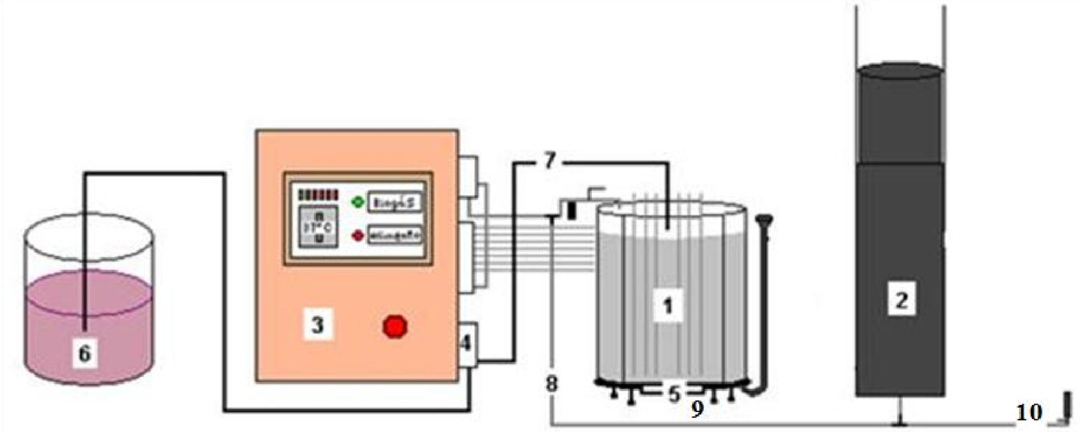

Fig. 1. Basic scheme of the perfect mixing continuous anaerobic digester (refered to in the text as CSTR). (1) Digester; (2) Gasometer; (3) Control system; (4) Feeding valve; (5) Heating plates; (6) Food tank; (7) Food current; (8) Biogas recirculation current; (9) Sampling; (10) Gas flares.

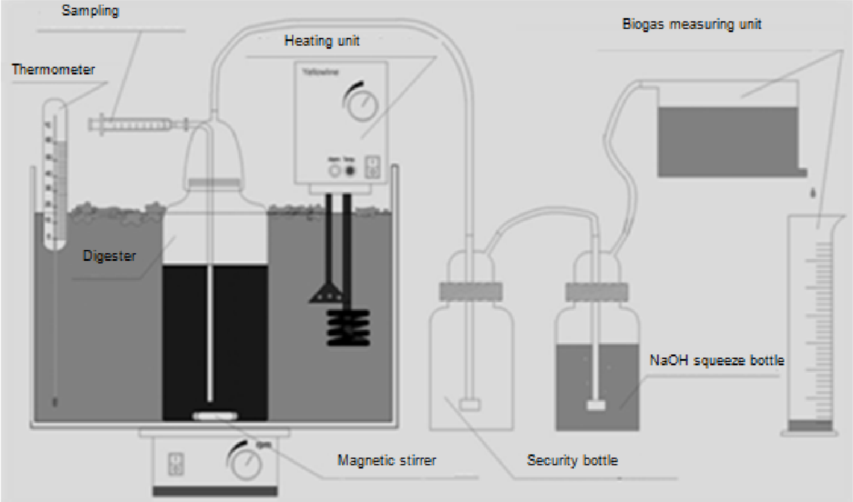

Fig. 2. Semicontinuous anaerobic digester.

2.2.4 Analytical method

A periodic sampling protocol was applied to the digesters during the experiments in order to record data concerning the following parameters: Chemical Oxygen Demand (COD), Biological Oxygen Demand per 5 days (BOD_5), Volatile Fatty Acids (VFA), alkalinity, pH, Total Solids (TS), Mineral Suspended Solids (MSS), Volatile Suspended Solids (VSS), Mineral Dissolved Solids (MDS), Volatile Dissolved Solids (VDS), and total organic carbon and nitrogen.

BOD_5, VFA, alkalinity, pH, TS, MSS, VSS, MDS and VDS were analyze according to the standard methods, whereas Nanocolor® kits and a portable PF-12 spectrophotometer (all from Macherey-Nagel Company) were used for data analysis concerning COD and total organic carbon and nitrogen.

The monitoring of all those analytical parameters allowed the tracking of the anaerobic digestion process and the detection of possible anomalies.

3 RESULTS

3.1 Anaerobic digestion experiments

As explained in the previous section, slaughterhouse wastes were degraded by an anaerobic digester operating in continuous regime, while a semicontinuous anaerobic digester was used for those from tomato processing industry. However, the same inoculum was used for both experiments, and particular feeding flow rates were considered for each biodigester: 250 and 270 ml/day for residues from tomato industry, and 150, 200 and 250 ml/day for those from slaughtering activities.

The feeding flow rate was progressively increased with a dual purpose. On the one hand, to ensure gradual bacterial acclimatization, and on the other hand to degrade as highest substrate flows as possible (which would result in a reduction of the Hydraulic Residence Time -HRT-). This allowed the anaerobic degradation of larger amounts of wastes in a given time, and would reduce construction costs in case experiments were conducted at industrial scale.

Table 4 Experimental results obtained with the optimal substrate flow.

Type of waste	HRT	m^3 methane/m^3 substrate day		m^3 biogas/m^3 substrate day		% degradation COD	
	days	Mean	Deviation	Mean	Deviation	Mean	Deviation
Slaughterhouse Continuous Digester 6 l capacity	24	16.9	1.11	22.53	1.47	69.95	2.80
Tomato Semicontinuous Digester 2 l capacity	8	9.68	2.10	12.91	2.79	55.09	7.43

HRT = Volume reactor/feeding flow.
%degradation COD = [(initial COD-final COD) / initial COD] x 100, with the initial COD defined as the COD of the residue at initial instant of biodigestion, and final COD defined as the COD of the effluent sludge at end of process.

The generated methane and biogas volumes were expressed in standard units to enable comparison of results from both experiments. The biogas obtained from both types of residues showed an excellent quality, with a methane volumetric content ranging from 71% to 82%, the mean methane volume being estimated as 75% for all experiments.

The remaining 25% was regarded as carbon dioxide, provided that the generated volumes of carbon monoxide, hydrogen and hydrogen sulphide were approached as negligible.

3.2 Estimates of methane and carbon dioxide emissions to the atmosphere if wastes were degraded by natural process

In order to estimate the volume of methane that would be released to the atmosphere if residues were naturally decomposed or dumped to landfills for putrefaction, the biogas production per ton residue (as well as methane and carbon dioxide volumes) were the same as in the hypothetical case of wastes undergoing an AD process in the bioreactors, provided that AD is an acceleration of the natural putrefaction process of organic matter under controlled surrounding conditions. Moreover, as AD was carried out at standard pressure and temperature conditions, all gas volumes were referred to them.

Experimental results regarding tomato industry wastes showed a biogas production rate of 12.91±2.79 m^3 biogas per m^3 feeding substrate and per day needed for degradation (see Table 4). As abovementioned, such biogas was composed of 75% methane and 25% carbon dioxide (mean values), and it can therefore be stated that wastes from tomato industry generate about 9.68±2.10 m^3 methane per m^3 feeding substrate per day, and about 3.23±0.70 m^3 carbon dioxide per m^3 feeding substrate per day.

Provided that degradation of residues from tomato industry takes 8 days in average under laboratory conditions, methane and carbon dioxide emissions released to the environment could be straightforwardly quantified.

Particular results for wastes from tomato processing industry in Extremadura by 2009 are listed in Table 5. It must be noted that only the average values were taken into account to compare the two degrading processes, i.e. natural conditions and anaerobic digestion.

Table 5. Biogas, methane and carbon dioxide volumes generated in 2009 by degradation of wastes from tomato processing industry in Extremadura.

Released biogás (m^3)		
minimum	average	maximum
85 008 000	108 444 000	131 880 000
Released methane (m^3)		
minimum	average	maximum
63 672 000	81 312 000	98 952 000
Released carbon dioxide (m^3)		
minimum	average	maximum
21 252 000	27 132 000	33 012 000

Table 4 shows that 22.53±1.47 m^3 biogas were obtained per m^3 slaughterhouse substrate and per day of degradation process (note that 24 days are needed in this particular case). As already pointed out, the average composition of biogas from slaughterhouse wastes was observed as 75% methane and 25% carbon dioxide. Therefore, the production rates of such gases can be straightforwardly calculated as 16.9±1.11 m^3 methane per m^3 substrate per day, and 5.63±0.37 m^3 carbon dioxide per m^3 substrate per day. Estimates of emissions due to degradation of slaughterhouse wastes are shown in Table 6.

Table 6. Biogas, methane and carbon dioxide volumes generated in 2009 by degradation of slaughterhouse wastes in Extremadura.

Released biogás (m^3)		
minimum	average	maximum
131 044 114	140 224 359	149 404 605
Released methane (m^3)		
minimum	average	maximum
98 275 306	105 183 829	112 092 353
Released carbon dioxide (m^3)		
minimum	average	maximum
32 737 689	35 040 530	37 343 371

3.3 Estimate of carbon dioxide emissions when using the generated methane as fuel.

The AD of wastes from the two sources under study (tomato processing industry and slaughtering activities) generated total volumes of 186 495 829 m^3 methane and 62 172 530 m^3 carbon dioxide by 2009. If such methane volume was assumed to be properly stored for further use as fuel, the volume of carbon dioxide that would be released to the atmosphere due to its combustion could be determined as follows.

Methane combustion is governed by the reaction:

$CH_4 + 2O_2 \rightarrow CO_2 + H_2O$ + heat (890 kJ/mol)

If the featuring parameters of methane (density 0.680 kg/m^3, molecular mass 0.016043 kg/mol) and carbon dioxide (density 1.870 kg/m^3, molecular mass 0.04401 kg/mol) are considered, and assuming one mol CO_2 per mol CH_4 as stated by Eq. (1), the combustion of the volume of methane obtained from the AD of agrifood wastes generated in Extremadura by 2009 would result in 347 891 t carbon dioxide and 1.85 x 10^9 kWh thermal energy.

Extra 116 263 t carbon dioxide directly generated by the AD process (25% of total biogas production, as already explained) should be added to the value expressed in the previous paragraph, which yields a final total carbon dioxide emission (due to both methane combustion and AD of agrifood wastes in Extremadura by 2009) of 464 154 t.

4. ESTIMATE OF THE ENVIRONMENTAL BENEFITS FROM THE ANAEROBIC DIGESTION PROCESS

As indicated in the preceding paragraphs, if wastes from the industries under study were dumped to the environment for natural degradation, 126 817 t methane and 116 263 t carbon dioxide would be released to the atmosphere.

Assuming methane as being 23 times more effective than carbon dioxide to absorb longwave radiation reradiated from the Earth, those 126 817 t methane would transform into 2 916 795 equivalent t carbon dioxide. According to this, the total carbon dioxide equivalent emission due to natural degradation (putrefaction) of these residues by 2009 would have reached 3 033 057 equivalent t. This amount might be compared to 464 154 t carbon dioxide generated by controlled AD of the residues (considering methane combustion to produce thermal energy). If the latter process had been carried out, the greenhouse effect would have been mitigated by 15.3% with respect to the hypothetical case of wastes being dumped to the environment for natural degradation.

5. CONCLUSIONS

The anaerobic digestion of wastes from tomato processing industry generates 12.91±2.79 m^3 biogas per m^3 substrate per day, obtained as 9.68±2.10 m^3 methane plus 3.23±0.70 m^3 carbon dioxide per m^3 substrate per day, with a hydraulic residence time of 8 days. The anaerobic digestion of these residues (tomato industry wastes) generated in Extremadura by 2009, under the assumption of generated methane being burned to produce 8.04x10^8 kWh useful thermal energy, would release only 202 417 t carbon dioxide to the atmosphere. If such residues were dumped to the environment for natural degradation (putrefaction), carbon dioxide emissions would reach 1 322 457 t, and of course no useful energy would be obtained from the controlled combustion of methane.

The treatment of slaughterhouse wastes by controlled anaerobic digestion would produce 22.53±1.47 m^3 biogas per m^3 substrate per day. Assuming that biogas production was obtained as 75% methane plus 25% carbon dioxide, methane and carbon dioxide production rates are therefore calculated as 16.9±1.11 and 5.63±0.37 m^3 per m^3 substrate per day, respectively, with a hydraulic residence time of 24 days. According to this, the anaerobic digestion of the residues generated by slaughtering activities in Extremadura in 2009 would cause carbon dioxide emissions to the atmosphere estimated as 261 737 t, instead of 1 710 600 t released if those residues were dumped into landfills for natural degradation. Moreover, the anaerobic digestion process would allow the production of 1.04x10^9 kWh useful energy.

If the combined emissions due to the anaerobic digestion of both types of residues were accounted for, it might be stated that anaerobic digestion would yield a 15.3% reduction of carbon dioxide emissions as compared to wastes being dumped to the environment for natural degradation. In addition, the former method would allow the production of 1.8x10^9 kWh useful energy.

Results showed that anaerobic digestion of agrifood wastes should not be regarded as only an efficient technique to produce useful energy (heat and/or electricity) from a renewable energy source (wet residual biomass), but also as a controlled degradation process with a notable contribution to the reduction of environmental pollution; in particular, to the reduction of methane emissions, a gas 23 times more effective than carbon dioxide to absorb longwave radiation from the surface of the Earth.

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