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ASSESSMENT OF ORGANIC WASTE MANAGEMENT METHODS THROUGH ENERGY BALANCE

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ABSTRACT

In Italy, the Organic Fraction of Municipal Solid Waste (OFMSW) is nowadays landfilled or processed through aerobic composting. The Italian towns currently support a high cost for OFMSW disposal and cause a high environmental impact, because of long distances travelled from towns to a few available landfills and fewer treatment places, as well as the used waste management methods. An interesting option for OFMSW is Anaerobic Digestion (AD), producing biogas and “digestate”. In this survey a theoretical biogas plant was placed near a town of Sicily Region (Italy), centralised with reference to the area considered for producing OFMSW. The distances travelled every year to transport OFMSW from the nine towns considered to the nearest composting plant and the biogas one were calculated using QGIS software. Therefore, the energy balance was computed for each of the four considered scenarios. Within the implementation of Integrated Solid Waste Management (ISWM) method, AD resulted in an energy balance much higher than that of aerobic composting. In fact, differently from composting, AD can significantly contribute to energy recovery, while retaining the nutrients in the digestate produced and reducing Greenhouse Gas (GHG) emissions. The use of a rational network of towns for OFMSW collection and transportation results relevant, in terms of increased energy balance, only in the case of composting. Therefore, if AD would be implemented as OFMSW management method, by means of biogas plants, each of them placed in an area including some towns, e.g. that considered in this survey, it could highly reduce the cost and the environmental impact of waste disposal.

Keywords: OFMSW, Centralised Anaerobic Digestion, Biogas, GIS, Energy Balance

1. INTRODUCTION

Waste management has become a worldwide problem over the last 30 years (Braber, 1995; Sakai *et al*., 1996; Lema and Omil, 2001; Habib *et al*., 2013; Cucchiella *et al*., 2014). The disposal at landfills is the main method to manage Municipal Solid Waste (MSW) in the world (He *et al*., 2005; Pognani *et al*., 2009; Rimaitytė *et al*., 2010; Dong *et al*., 2014).

Moreover, the Anaerobic Digestion (AD) of the biodegradable Organic Fraction of the landfilled MSW causes several environmental problems, like odours due to Volatile Organic Compounds (VOCs) and leachate, the presence of vectors (i.e. insects, rodents and birds) determining public health hazards and plant toxicity (Thorneloe and Pacey, 1994). All these negative impacts and the long time required to stabilise raw materials (care period) are the major issues that make landfills unsustainable (Pognani *et al*., 2009). The Intergovernmental Panel of Climate Change (2006) reported that more than 60% of the total MSW produced in the world is landfilled: 67% in Europe, 69% in Africa, 61% in America, 63% in Asia (Dong *et al*., 2014) and 75% in Oceania. Within EU, Greece is the only old Member State where landfills have a share higher than 80%, while all the other EU countries having so high

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landfill use are new Member States (Cucchiella *et al*., 2014). The European Council Directive on waste landfills requires Member States to plan strategies for reducing the amount of biodegradable MSW transferred to landfills to only 35% of that produced in 1995 over a 15-year period (EU, 1999). Moreover, according to the Directive 2006/12/EC, "the use of waste as a source of energy" must be encouraged by Member States as a good manner to avoid landfill and to prevent pollution (Novarino and Zanetti, 2012). The compliance to the above Directives, as well as the fact that new landfill sites are difficult to find, because of shortage of utilisable land and opposition of people living nearby, is diverting the use of the Organic Fraction of Municipal Solid Waste (OFMSW) to other purposes (Rimaitytė *et al*., 2010; Novarino and Zanetti, 2012). The high moisture content and low calorific power of OFMSW do not allow energy reclaim by its direct combustion (Chang *et al*., 1995; Rimaitytė *et al*., 2010). Furthermore, as OFMSW is a biodegradable material, the alternative management methods to the disposal at landfills or incineration are biological processes, such as aerobic composting and AD (Pognani *et al*., 2009; 2012).

Aerobic composting has been the main method for managing OFMSW and has been used increasingly over the last 10 years.

As the new EU policy aims at increasing the production of renewable energy, using also organic wastes, the AD of OFMSW has become very popular (Novarino and Zanetti, 2012; Tudisca *et al*., 2013). Furthermore, AD is nowadays a very interesting process in Europe, where the number of biogas plants is increasing (Pognani *et al*., 2009; Novarino and Zanetti, 2012; Comparetti *et al*., 2013a).

The chemical composition of OFMSW and, therefore, the yield of AD process, is influenced by several factors, e.g. climate, collection frequency and method, season, cultural practices, changes in its solid components (Tchobanoglous *et al*., 1993; Pavan *et al*., 2000; Saint-Joly *et al*., 2000; Bolzonella *et al*., 2003a; 2003b; Mace *et al*., 2003; Bolzonella *et al*., 2005; Grillone *et al*., 2014). Several papers focused on aspects of AD of organic wastes according to their origin, e.g. market (Mata-Alvarez *et al*., 1992), fruit and vegetable (Bouallagui *et al*., 2005), household (Krzystek *et al*., 2001), food (Kim *et al*., 2000), kitchen waste (Rao and Singh, 2004), bio-waste (Gallert *et al*., 2003) and OFMSW (Bolzonella *et al*., 2005).

A high yield, in terms of biogas and high quality compost production, is generally associated with the treatment of Separately Collected (SC) or Source Sorted (SS) OFMSW, while Mechanically Sorted (MS) OFMSW gives lower biogas production and a residual material which has to be disposed at landfills or incinerated (CITEC, 2004). Two main simple technologies have been used for the rapid AD of OFMSW: sequential leach bed bio-reactor (O'Keefe and Chynoweth, 2000) and Continuous Stirred-Tank Reactor (CSTR) (Pavan *et al*., 2000) or Batch bio-reactor (Lissens *et al*., 2001; Kim *et al*., 2002). Sustainable methods for waste treatment, aimed at recycling and feeding back nutrients to soils, will produce a high benefit for the environment (Braber, 1995; Sakai *et al*., 1996; Lema and Omil, 2001).

The Centralised Anaerobic Digestion (CAD) of OFMSW inside a bio-reactor, centralised with reference to the area of waste collection, allows to produce methane, determining a net energy gain and a bio-fertiliser from the process residuals (Dagnall, 1995; Hamzawi *et al*., 1999; Edelmann *et al*., 2000; Sonesson *et al*., 2000). The centralised or joint biogas plants are usually of large scale, with digester capacities ranging from a few hundreds of m^3 up to several thousands of m^3. Denmark was one of the pioneer countries in developing agricultural centralised biogas plants since the early 1980 s. A joint biogas plant allows the valorisation of resources, the co-digestion of manure and other organic wastes, the nutrient recycling and redistribution. Thus, the biogas production cycle generates intertwined agricultural and environmental benefits, like renewable energy production, cheap and environmentally healthy organic waste recycling, lower greenhouse gas emission (i.e. CH_4, N_2O and NH_3), pathogen reduction through sanitation, improved fertilisation efficiency (Holm-Nielsen *et al*., 1997; Amon *et al*., 2006; Holm-Nielsen *et al*., 2009; Comparetti *et al*., 2013a; Cucchiella *et al*., 2014; Eriksson *et al*., 2014), less nuisance from odours and flies (Birkmose, 2007), economic advantages for farmers. The digested biomass is transferred to storage tanks, which are usually covered with a gas proof membrane, in order to reclaim the remaining biogas (Holm-Nielsen *et al*., 2009). The biogas produced, rich in methane, would be used either on-site or very near the plant. The possible uses of biogas are: transport to the natural gas distribution pipeline; upgrading into vehicle fuel (like in Sweden); Combined Heat and Power (CHP) generation, for producing hot water, to be used by the heating equipment of the consumers in the surrounding area and electricity, to be sold and transferred to the grid (Dagnall, 1995; Holm-Nielsen *et al*., 1997; Nielsen *et al*., 2002; Persson *et al*., 2006; Novarino and Zanetti, 2012; Comparetti *et al*., 2013a). Some of the thermal energy is used inside the biogas plant for process heating (Holm-Nielsen *et al*., 1997). These biogas plants could serve either a single large farm or several ones, typically with in a radius of 10 km ca., because of the high moisture content of the feedstock (6-10% dry matter). Instead, the feedstock having high dry matter (more than 25%), e.g. agro-industrial waste and poultry litter, could be transported for higher distances, up to 50 km (Dagnall, 1995; Bolzonella *et al*., 2006). The co-digestion of OFMSW and sewage sludge or other substrates (agro-industrial by-products, e.g. dairy and olive oil industry residues) was developed in the recent years, in order to obtain multiple waste treatment in a plant and an increasing methane content inside biogas (Fantozzi and Buratti, 2011).

The biogas plants can be equipped with installations for separating the fibre and liquid fractions of the biomass digested ("digestate"). The liquid fraction of digestate is stored inside tanks and, then, used in the farms as a pathogen free organic fertiliser (MAFF, 1986; Novarino and Zanetti, 2012). Farmers receive back only the amount of digestate which they are allowed to apply on their fields, according to the regulation on nutrient loading/ha (Holm-Nielsen *et al*., 2009). Thus, farmers can save money for buying inorganic fertilisers (Dagnall, 1995; Novarino and Zanetti, 2012; Eriksson *et al*., 2014). Although the fibre fraction of digestate has an immediate value as soil conditioner (because it increases the soil organic matter content and improves its structure), it may be further processed to produce a higher value organic compost (Dagnall, 1995). This process, called aerobic "polishing", is able to reduce odours, pathogens, moisture and carbon content in the digestate (McDougall *et al*., 2001; Tchobanoglous *et al*., 2002).

Generally OFMSW allows a high biogas yield inside bio-reactors. When OFMSW consists of a high ratio of garden waste, it has low pH, water content and nutrient concentrations (Rivard *et al*., 1989; 1990). Instead, when OFMSW consists of a high ratio of food waste, it contains high concentrations of proteins, originating also ammonia, which can inhibit AD, especially when the digestate is recirculated in the bio-reactor (Gallert and Winter, 1997). Furthermore, OFMSW can contain considerable amounts of heavy metals and xenobiotic compounds (Braber, 1995; Hartmann and Ahring, 2003). Both "wet" and "dry" anaerobic technologies have been used as part of Mechanical-Biological Treatment (MBT) (Mata-Alvarez, 2003). There are also examples of the processing of mixed source segregated biodegradable wastes, like kitchen and garden wastes (Archer *et al*., 2005), but there are a few reports on AD plants entirely operating on household food waste separated at source (Banks *et al*., 2011). The interest in this approach is growing in Europe, due to rising energy costs associated with the processing of wet waste, the requirement to meet the targets of the EU Landfill Directive (99/31/EC) (EU, 1999) and the need to comply with regulations for the disposal of animal by-products (EU, 2002). When AD is used to process waste separated at source, it produces not only biogas but also a high quality nutrient-rich organic fertiliser (Banks *et al*., 2011). According to the regulations of many European countries, whether the waste is not separated at source but the organic fraction is reclaimed through a MBT plant, the digestate produced is not allowed to be applied on land (Stretton-Maycock and Merrington, 2009). As a consequence, government and industry are strongly interested in the methods of AD process of household food waste separated at source (Banks *et al*., 2011).

Waste management is nowadays a worldwide problem to be solved, yet. In fact, the landfill sites have been or will be filled in with MSW very soon in Italy and elsewhere, where people don't accept the use of new sites in their municipal land, while the former landfills have to be recovered (Rimaitytė *et al*., 2010). Moreover, the measures aimed at promoting segregated waste collection were only scarcely implemented in Italy, where the environmentalist movements always fight against the building of incinerators. As a consequence, the inefficient waste management has often caused public health problems in whole cities (Naples, Palermo, etc.), from where sometimes waste has been transported abroad (Germany, etc.).

In the above perspective the aim of this survey is "to make a virtue of necessity": to valorise the Organic Fraction of MSW, instead of treating it as a not segregated waste. The motivation behind this survey is to provide towns with a criterion for selecting, among the organic waste management methods, that able to optimise the energy balance. Thus, by means of this criterion, town administrators could choice an alternative and sustainable method for OFMSW management, enabling to reduce the high cost and the environmental impact of waste disposal.

2. EXPERIMENTAL PROCEDURES

In this survey the energy balance of four scenarios for the management of the OFMSW produced in an area of Sicily Region (Italy) was evaluated and compared.

This area includes nine towns of Palermo province, where 82 thousands of inhabitants live: Altofonte, Belmonte Mezzagno, Bolognetta, Marineo, Misilmeri, Piana degli Albanesi, San Cipirello, San Giuseppe Jato and Santa Cristina Gela.

The mass of MSW (M_{MSW}) produced per year was calculated according to the number of inhabitants N_{inh} and the waste mass produced by one person per year m_{inh} (Equation 1):

$$M_{MSW} = N_{inh} \cdot m_{inh} \qquad (1)$$

Where:

N_{inh} = Number of inhabitants;

m_{inh} = Mass of MSW produced by one inhabitant per year (kg year^{-1}) with assumed MSW mass of 1.2 kg produced by one person per day.

A sample of OFMSW was collected in Marineo town and transported to the laboratory of the Institute of Energy and Biotechnology Engineering of Aleksandras Stulginskis University in a day of March 2012.

The Total Solid (TS) concentration in OFMSW was determined, by drying the above sample in an oven at 105±2°C temperature for 24 h, as well as Volatile Solid (VS) concentration, by burning biomass at 500°C temperature. Total organic Carbon concentration (CT) was determined, by using an analyser TOC II, as well as Total Nitrogen concentration (NT), by using a Kjeldal apparatus.

AD tests were carried out in a laboratory scale anaerobic digester under controlled temperature (38±0.5°C). The laboratory digester consists of stainless steel vessels (having 20 litre volume) with substrate mixer (having mixing intensity of 60 min^{-1}). The biogas produced was collected at the top of the digester and conveyed through the drum type flow meter to a gasholder (25 litre Tedlar® bag). Later the biogas collected was analysed by using a Schmack SSM 6000 biogas analyser.

The following four scenarios for waste management have been considered:

(1) currently used method for OFMSW management, whereas this waste collected in each town is transported to the nearest composting plant (in this scenario often the trucks must travel even if they are only partially filled in with OFMSW, so that the transportation cost is not optimised);
(2) method for OFMSW management using an efficient and rational network of towns for waste collection and transportation, similar to that proposed by (Menikpura *et al*., 2013), to the nearest composting plant, aimed at minimising its cost and fuel consumption;
(3) method for OFMSW management, whereas this waste collected in each town is transported to a theoretical biogas plant placed at Marineo (Palermo);
(4) method for OFMSW management, whereas this waste collected in each town is transported to a theoretical biogas plant placed at Marineo, using the above efficient and rational network of towns for waste collection and transportation.

In the considered scenarios the travelled distance for waste transportation was computed by using the plugin Road Graph for QGIS software. The selected tracks can be displayed by using Google Maps or Google Earth software.

According to the Italian law, the OFMSW produced and collected can be stored for a maximum time of 72 h, then it must be transferred to a landfill or any treatment plant. Therefore, relying on the OFMSW produced and collected in each town during a week, the truck loading capacity and the above law restriction, the number of travels needed was computed for each scenario.

The scenarios 2, 3 and 4 are hypotheses aimed at improving OFMSW management with reference to the current scenario 1.

In the scenarios 1 and 2 OFMSW is transported to two Sicilian composting plants, placed at Castelbuono (Palermo) and Sciacca (Agrigento), where it is treated for producing compost.

In the scenario 2 four groups of towns, each of them using the same truck, addressed to the nearest composting plant, were considered:

- San Cipirello and San Giuseppe Jato, from where OFMSW is transported to Sciacca;
- Bolognetta and Marineo, from where OFMSW is transported to Castelbuono;
- Altofonte, Piana degli Albanesi and Santa Cristina Gela, from where OFMSW is transported to Sciacca;
- Belmonte Mezzagno and Misilmeri, from where OFMSW is transported to Castelbuono (**Fig. 1**).

Fig. 1. Map presenting the towns where OFMSW is collected, (1) Altofonte, (2) Santa Cristina Gela, (3) Piana degli Albanesi, (4) San Giuseppe Jato, (5) San Cipirello, (6) Belmonte Mezzagno, (7) Misilmeri, (8) Bolognetta, (9) Marineo; two composting plants, (A) Castelbuono and (B) Sciacca; (C) Marineo theoretical biogas plant

The scenarios 3 and 4 follow the typical centralised Danish pattern, whereas OFMSW is transported from each town to a centralised biogas plant, to be built at Marineo.

In these two scenarios the biogas produced is converted in CHP, while the digestate is stored inside tanks and, then, used as fertiliser.

In the scenario 4 OFMSW is transported, by means of the same truck, from each of the four groups of towns reported in the scenario 2, to the theoretical biogas plant placed at Marineo.

In all scenarios, within the cycle of organic waste management, the energy input is needed for the steps of waste collection, pre-treatment, transportation to the processing plant and treatment process. This energy input depends on the following factors: distance from the waste production site to the processing plant, transportation type (presence or absence of a rational network of towns), design of treatment plant and processing technology.

As OFMSW can be processed into compost (in a composting plant) or biogas (in a bio-reactor), the energy input of waste treatment technology Ein (composting or AD, respectively) is the sum of the energy input for transportation E_{tr} and that for processing technology E_{techn} (Equation 2):

$$E_{in} = E_{tr} + E_{techn} \quad (2)$$

Where:

E_{tr} = Energy input for OFMSW transportation to the processing plant (J t^{-1} of treated waste);

E_{techn} = Energy input for OFMSW processing technology (J t^{-1} of treated waste).

In all scenarios trucks of 12 t loading capacity (15 m^3 hopper volume) were considered for OFMSW transportation. As far as the fuel consumption, it is difficult to know the effective data of used machines, both trucks and tractors (Febo and Pessina, 1995). According to EUCAR (2007) a fully loaded new truck consumes 23.5 l of diesel fuel 100 km^{-1}, assuming the density of the fuel 832 kg m^{-3} and its heating value 43.1 MJ kg^{-1}. Fuel consumption was calculated according to the used loading capacity of the truck.

The AD results of OFMSW were evaluated by means of the following indicators: biogas production intensity *b*, biogas yield from biomass *BM*, biogas yield from biomass *TS BTS*, biogas yield from biomass *VS BVS*, energy obtained from biomass *eM*, from biomass *TS eTS* and from biomass *VS eVS*. Biogas production intensity *b* indicates the volume of biogas produced during the time of biomass biological degradation. Biogas yield from biomass *BM*, from biomass *TS BTS* and from biomass *VS BVS* was calculated by means of the following Equations 3 to 5 (Navickas *et al*., 2003):

$$B_M = \frac{b_{dt}}{m} \tag{3}$$

$$B_{TS} = \frac{b_{dt}}{m_{TS}} \tag{4}$$

$$B_{VS} = \frac{b_{dt}}{m_{VS}} \tag{5}$$

Where:

b_{dt} = Volume (l) of biogas produced (in laboratory) during the time interval dt (duration of biomass biological degradation);
m = Mass (kg) of the biomass sample analysed;
m_{TS} = Mass (kg) of TS in the biomass sample;
m_{VS} = Mass (kg) of VS in the biomass sample.

The energy obtained during AD from biomass e_M, e_{TS}, e_{VS} was determined by means of the following Equations 6 to 8:

$$e_M = B_M \cdot e_b \tag{6}$$

$$e_{TS} = B_{TS} \cdot e_b \tag{7}$$

$$e_{VS} = B_{VS} \cdot e_b \tag{8}$$

Where:

e_b = Energetic value of biogas (MJ m^{-3}), which depends on methane concentration in biogas (%).

The energetic value of biogas was determined by means of the following Equation 9:

$$e_b = 0.0353 \cdot \frac{C_M}{100} \tag{9}$$

Where:

C_M = Methane concentration in biogas (%)

The energy efficiency of OFMSW conversion into biogas was determined as follows (Equation 10):

$$\varepsilon = \frac{(e_M - E_{in})}{E_{in}} \tag{10}$$

3. RESULTS AND DISCUSSION

The surveyed towns of Palermo province produce 35.9 thousand tonnes of MSW per year (**Table 1**). OFMSW was supposed to be the 30% of MSW, that is equal to 10.8 thousand tonnes, of which only the 70% is collected (Sicilian Region, 2010; Comparetti *et al*., 2012). Therefore, 7.5 thousand tonnes of OFMSW per year are collected and available for composting or AD.

The chemical composition of OFMSW sample resulted as follows: 15.6% TS; 91.1% organic materials (in TS); 5.69% organic carbon; 0.328% total nitrogen (TS). Generally optimum C/N ratios in anaerobic digesters are in the range of 20-30 (Themelis and Verma, 2004; Ward *et al*., 2008). The C/N ratio of the OFMSW analysed resulted 17.4 and, therefore, optimal for AD process. Nevertheless, in a review article (Ward *et al*., 2008) reported that lower C/N ratios (approximately 9) are also accepted by anaerobic bacteria after an acclimation period.

During AD tests, whose duration was 12 days, the biogas yield obtained from biomass resulted 104.6 l kg^{-1} (**Table 2 and Fig. 2**). The methane concentration in biogas was 61.9%. The biogas yield from organic matter was 712.7 l kg^{-1} and, therefore, comparable with the results of Banks *et al*. (2011), i.e., 642 l kg^{-1} with a methane content of 62% and Bolzonella *et al*. (2006), i.e. 700 l kg^{-1} with a biogas yield from biomass of 180 l kg^{-1} and a methane content of 56% from sorted OFMSW.

The biogas yield from organic matter could be temporally variable, due to changing life style and consumed food composition. The results obtained by Mata-Alvarez *et al*. (1992), using organic waste coming from a large food market, show that biogas yield from a similar feedstock reaches 487 l kg^{-1}. The energy obtained from biomass (e_M) resulted 2.28 MJ kg^{-1}, that from dry matter (e_{SM}) 14.68 MJ kg^{-1} and that from organic matter (e_{SOM}) 16.13 MJ kg^{-1}.

In the scenario 1 the total travelled distance for OFMSW transportation per year resulted 191,748 km, while in the scenario 3 this distance decreased to 42,432 km (**Table 3**).

With respect to the total travelled distance per year recorded in the scenario 1, in the scenarios 2 and 4, having a rational network of towns for OFMSW transportation to the nearest composting (scenario 2) or biogas plant (scenario 4), this distance decreased to 111,146 and 28,954 km, respectively (**Table 3**).

In the scenario 2 the total travelled distance per year decreased by 42% with respect to the scenario 1, as well as the energy input for OFMSW transportation, reduced by 40% (**Table 4**). In the scenario 3 the total travelled distance per year and the energy input for waste transportation decreased by 78% with respect to the scenario 1.

In the scenario 4 the total travelled distance per year and the energy input for transportation decreased by 74% with respect to the scenario 2, even if the same rational network of towns for OFMSW collection and transportation is used in both scenarios.

Thus, the scenario 1 is the worst one, in terms of energy input for transportation, but the adoption of a rational network for this operation can significantly reduce this input, as it is shown in the scenario 2.

The energy input for OFMSW composting technology resulted 1751 GJ per year and, therefore, higher by 29% with respect to AD technology (1240 GJ per year). Furthermore, the anaerobic treatment technology produces biogas, which resulted in an energy output of 17198 GJ.

The highest total energy balance per year was recorded in the scenarios 4 and 3, 15738 and 15647 GJ, respectively (**Table 4**).

The scenarios 1 and 2 showed no energy production capacity but only energy usage for transportation and composting, so that they resulted in a negative total energy balance (**Fig. 3**). These results comply with those obtained by Corsten *et al*. (2013). In fact, differently from composting, AD can significantly contribute to energy recovery, while retaining the nutrients in the digestate produced and reducing Greenhouse Gas (GHG) emissions (Corsten *et al*., 2013).

In the four considered scenarios the energy input for waste treatment technology per inhabitant was calculated according to the number of inhabitants of each town (**Fig. 4**). The results showed that the town of Santa Cristina Gela has the highest energy input per inhabitant in all scenarios, as it has the lowest number of inhabitants and a high transportation distance.

In all towns the scenarios 1 and 2 showed the highest energy input for waste treatment technology per inhabitant, ranging from 0.113-3.450 (scenario 1) to 0.094-2.856 (scenario 2), with an averaged value of 0.769 GJ/inhabitant (scenario 1) and 0.636 GJ/inhabitant (scenario 2). Instead, the scenarios 3 and 4 showed a lower averaged energy input per inhabitant, 0.375 GJ/inhabitant and 0.350 GJ/inhabitant, respectively.

The OFMSW composting technology requires energy input, which was calculated to be 232 MJ t^{-1}. Energy input for AD resulted 165 MJ t^{-1}, which can be compared to the results obtained by Bolzonella *et al*. (2006) during the AD of sorted MSW (72 kWh t^{-1}, equal to 259.2 MJ t^{-1}).

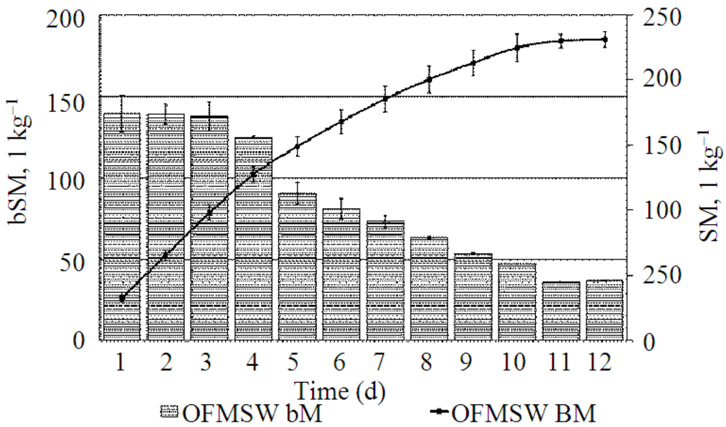

Fig. 2. Biogas yield Obtained From biomass (OFMSW) during AD tests: the histograms are the daily yield b_M, while the curve is the total cumulated yield B_M

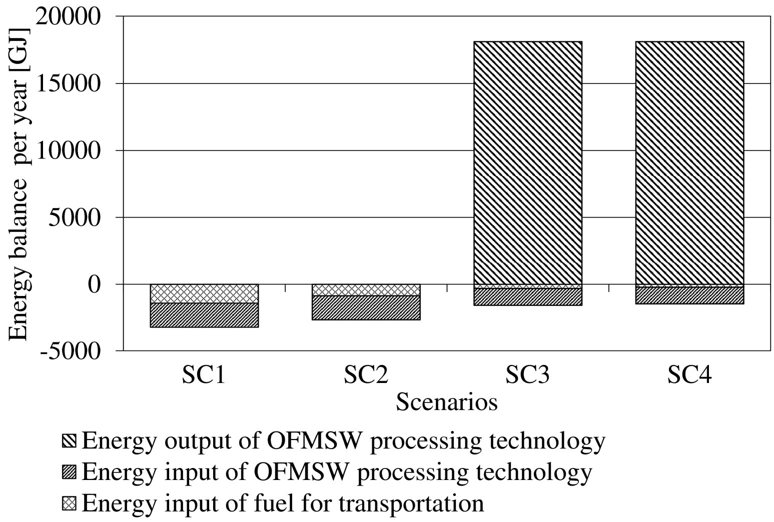

Fig. 3. Total energy balances in the four considered scenarios

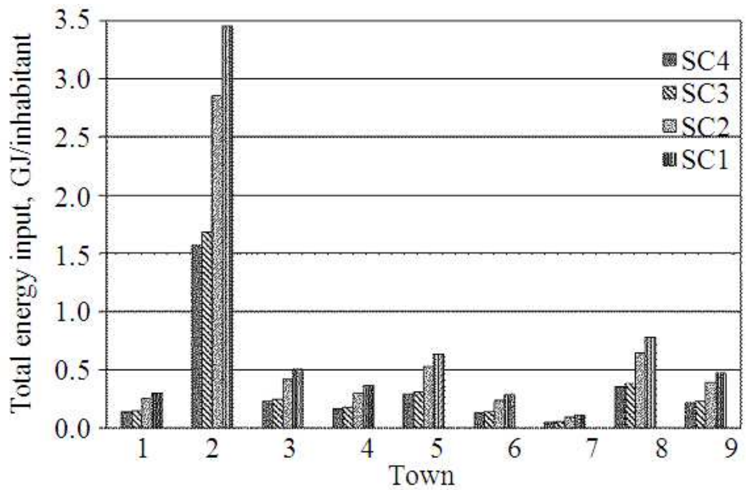

Fig. 4. Energy input for waste treatment technology per inhabitant for the surveyed towns in the four considered scenarios

Table 1. Number of inhabitants and waste mass produced per year

Town	Inhabitants	MSW[t]	OFMSW [t]	Collected OFMSW [t]
Altofonte	10438	4572	1372	960
Santa Cristina Gela	928	406	122	85
Piana degli Albanesi	6325	2770	831	582
San Giuseppe Jato	8799	3854	1156	809
San Cipirello	5016	2197	659	461
Belmonte Mezzagno	11190	4901	1470	1029
Misilmeri	28307	12398	3720	2604
Bolognetta	4096	1794	538	377
Marineo	6791	2974	892	625
Total	81890	35866	10760	7532

Table 2. Results of AD tests

Indicator	Rate	Value
Biogas yield from biomass, B_M	$l \cdot kg^{-1}$	104.60
Biogas yield from dry matter, B_{SM}	$l \cdot kg^{-1}$	672.30
Biogas yield from organic matter, B_{SOM}	$l \cdot kg^{-1}$	712.70
Methane concentration in biogas, C_M	%	61.90
Energetic value of biogas, e_b	$MJ \cdot m^{-3}$	21.80
Energy obtained from biomass, e_M	$MJ \cdot kg^{-1}$	2.28
Energy obtained from dry matter, e_{SM}	$MJ \cdot kg^{-1}$	14.68
Energy obtained from organic matter, e_{SOM}	$MJ \cdot kg^{-1}$	16.13

Table 3. Travelled distances (km) for OFMSW transportation from the collection town (1 Altofonte, 2 Santa Cristina Gela, 3 Piana degli Albanesi, 4 San Giuseppe Jato, 5 San Cipirello, 6 Belmonte Mezzagno, 7 Misilmeri, 8 Bolognetta, 9 Marineo) to the nearest composting (A Castelbuono, B Sciacca) or theoretical biogas plant (C Marineo)

	Scenario 1									
Town→Composting plant	1→B	2→B	3→B	4→B	5→B	6→A	7→A	8→A	9→A	Total
Distance to plant	85	82	76	65	61	89	82	89	93	
Distance per year	20740	20008	18544	15860	14884	21716	35588	21716	22692	
	191748									
	Scenario 2									
Towns→Composting plant	1+2+3→B			4+5→B		6+7→A		8+9→A		Total
Distance to plant	101			65		89		95		
Distance per year	27472			13780		53934		15960	111146	
	Scenario 3									
Town → Biogas plant	1→C	2→C	3→C	4→C	5→C	6→C	7→C	8→C	9→C	Total
Distance to biogas plant	24	13	18	32	33	21	14	6	2	
Distance per year	5856	3172	4392	7808	8052	5124	6076	1464	488	42432
	Scenario 4									
Town → Biogas plant	1+2+3→C			4+5→C		6+7→C		8+9→C		Total
Distance to biogas plant	29			33		21		8		
Distance per year	7888			6996		12726		1344		28954

Table 4. Results of AD tests

Indicator	SC1	SC2	SC3	SC4
Total travelled distance [km]	191748	111146	42432	28954
Used fuel [l]	39245	23593	8685	6147
Energy input for OFMSW transportation [GJ]	1407	846	311	220
Energy input for OFMSW processing technology [GJ]	1751	1751	1240	1240
Energy output from OFMSW processing technology [GJ]	0	0	17198	17198
Total energy balance [GJ]	-3158	-2597	15647	15738

4. CONCLUSION

Waste management is a key element contributing to a sustainable and efficient resource use, because it includes waste prevention and reuse, as well as recycling of products (Corsten *et al.*, 2013).

The Directive 75/442/EEC defines a hierarchy of five waste management options, which must be applied by EU Member States: (1) waste prevention; (2) waste reuse; (3) waste recycling; (4) waste recovery, including the recovery of part of the energy embodied inside raw materials through AD; (5) safe waste disposal at landfills. The implementation of the above hierarchy is aimed at preventing and reducing waste production, avoiding, eliminating and preventing the causes of environmental impact, preventing GHG emissions, saving energy, protecting resources, creating new jobs and developing green energy technology (Menikpura *et al*., 2012; Corsten *et al*., 2013; Cucchiella *et al*., 2014).

Yet, a combination of treatment methods to manage the different waste fractions, e.g. recycling and AD, is required for a sustainable MSW management

(Liamsanguan and Gheewala, 2008; Bahor *et al*., 2009; Tabata *et al*., 2011; Hoornweg and Bhada-Tata, 2012). This approach, known as Integrated Solid Waste Management (ISWM), includes the source-separation of waste made by residents, an efficient collection and transportation network (similar to the rational network of towns used in this survey), the recovery of useful materials and energy, as well as the disposal of residual waste (Kathiravale and Yunus, 2008; Menikpura *et al*., 2012).

OFMSW contaminates recyclable materials in combined waste collection methods and releases methane to the atmosphere when landfilled. Methane has a Global Warming Potential (GWP) 23 times higher than that of carbon dioxide over a 100-year period (Lema and Omil, 2001) and therefore, significantly contributes to climate change (Browne and Murphy, 2013).

About 50% of MSW is nowadays landfilled, whereas a content of 30% ca. of OFMSW (unless paper and cardboard) is included in this waste (Tilche and Malaspina, 1998).

Among Southern Europe countries, MSW generation has recently increased in Spain, as a result of improved living standards, so that management measures are required to minimise the impact of MSW on the environment. The OFMSW produced in Spain, that is between 40 and 45% of the MSW, is suitable to be used for producing electricity through AD and CHP plants. In fact, 8.5 million tonnes ca. of biological waste were processed in Spanish treatment plants in 2006 (Fernandez Rodriguez *et al*., 2012).

Furthermore, a very high increase of anaerobically digested OFMSW is envisaged in the next future, especially as a consequence of the GHG emission reduction agreed during Kyoto summit: a daily reduction of 180,000 tonnes of CO_2 equivalents can be estimated as contribution of AD, that is 30% ca. of the global emission reduction agreed during this summit (Tilche and Malaspina, 1998).

As a result of implementing an appropriate ISWM method, organic waste landfilling will be avoided and, therefore, the release of methane to atmosphere will be prevented, while resources such as energy and materials will be recovered and GHG emissions will be mitigated (Menikpura *et al*., 2013).

OFMSW is one of the largest waste fractions produced yearly in Italy, as well as in other European countries. 11 million tonnes ca. of OFMSW are produced yearly in Italy but only 1% ca. is currently treated inside AD plants. A large fraction of this OFMSW, 50% w/w ca., together with other wastes, is disposed at landfills. Even if landfills usually have biogas recovery facilities, 1700-2400 GWh ca. of potential renewable energy per year is lost (Di Maria *et al*., 2012).

In Sicily, in 2011, 5 millions ca. of inhabitants produce 2 million tonnes ca. of MSW per year (430 kg/person/year), of which the 37% (159 kg/person/year) can represent the organic fraction, even if the OFMSW treated is only the 3% ca. of MSW (Comparetti *et al*., 2013b; Cucchiella *et al*., 2014).

Within EU, Ireland, having a population of 4.6 millions, similar to Sicilian one, generates 3 million tonnes ca. of MSW per year (652 kg/person/year), 2/3 of which are considered biodegradable. Food waste makes up 25% ca. of domestic household waste and 42% of commercial waste. It is estimated that 820,000 t/year ca. of food waste (178 kg/person/year) are generated in Ireland, whereas the catering sector produces over 100,000 t/year of food waste (Browne and Murphy, 2013).

In the above perspective, within the implementation of ISWM method, the results of this survey, in terms of energy balance of the two considered processes of OFMSW treatment, show that AD has an energy efficiency much higher than that of aerobic composting.

Moreover, the use of a rational network of towns for OFMSW collection and transportation results relevant, in terms of increased energy balance, only in the scenarios where this waste is aerobically treated, while it did not significantly affect the scenarios where OFMSW is converted into biogas and digestate.

Furthermore, in the scenarios where OFMSW is anaerobically digested, the highly positive energy balance obtained would be increased if also the energy saved for replacing the manufactured fertilisers with the digestate produced, were included among the energy inputs.

This study contributes to solve the problem of waste disposal, by demonstrating the usefulness of a criterion, based on energy balance. This criterion enables to identify a sustainable method for OFMSW management, i.e. AD, providing both economic and environmental benefits.

In fact, based on the results of this survey, if the Italian towns, that support a high cost for OFMSW transportation to landfills or composting plants and the subsequent treatment, would implement AD, could achieve a high saving. At the same time the environmental benefits for all citizens would be the reduction of GHG emissions, as well as soil and ground water pollution by leachate.

The limitation of implementing the results of this study is "ecomafia", that is the mafia involved in environmental business and, therefore, controlling the waste management. The "criminal systems" (as defined by the judge Roberto Scarpinato) are complex illegal networks including policy makers, entrepreneurs, professionals and traditional mafia men (OALL, 2011).

Therefore, a cultural change is needed, firstly in citizens and secondly in policy makers, entrepreneurs and professionals, in order to optimise the separate waste collection and the subsequent recycling, as well as valorise OFMSW through biogas and digestate production.

5. REFERENCES

Amon, B., V. Kryvoruchoko, G. Moitzi and T. Amon, 2006, Greenhouse gas and ammonia emission abatement by slurry treatment. Int. Cong. Series, 1293: 295-298. DOI: 10.1016/j.ics.2006.01.069

Archer, E., A. Baddeley, A. Klein, J. Schwager and K. Whiting, 2005. MBT: A Guide for Decision Makers-Processes, Policies and Markets. Juniper Consulting, Uley, UK.

Bahor, B., M.V. Brunt, J. Stovall and K. Blue, 2009. Integrated waste management as a climate change stabilization wedge. Waste Manage. Res., 27: 839-849. DOI: 10.1177/0734242X09350485

Banks, C.J., M. Chesshire, S. Heaven and R. Arnold, 2011. Anaerobic digestion of source-segregated domestic food waste: Performance assessment by mass and energy balance. Bioresource Technol., 102: 612-620. DOI: 10.1016/j.biortech.2010.08.005

Birkmose, T., 2007. Digested manure is a valuable fertilizer. Proceedings of European Biogas Workshop-the Future of Biogas in Europe III, June14-16, University of Southern Denmark, Esbjerg, Denmark, pp: 89-93.

Bolzonella, D., L. Innocenti, P. Pavan, P. Traverso and F. Cecchi, 2003a. Semi-dry thermophilic anaerobic digestion of the organic fraction of municipal solid waste: Focusing on the start-up phase. Bioresource Technol., 86: 123-129. DOI: 10.1016/S0960-8524(02)00161-X

Bolzonella, D., P. Battistoni, J. Mata-Alvarez and F. Cecchi, 2003b. Anaerobic digestion of organic solid wastes: Process behaviour in transient conditions. Water Sci. Technol., 48: 1-8.

Bolzonella, D., P. Pavan, F. Fatone and F. Cecchi, 2005. Anaerobic fermentation of organic municipal solid wastes for the production of soluble organic compounds. Ind. Eng. Chem. Res., 44: 3412-3418. DOI: 10.1021/ie048937m

Bolzonella, D., P. Pavan, S. Mace and F. Cecchi, 2006. Dry anaerobic digestion of differently sorted organic municipal solid waste: A full-scale experience. Water Sci. Technol., 53: 23-32. DOI: 10.2166/wst.2006.232

Bouallagui, H., Y. Touhami, R. Ben Cheikh and M. Hamdia, 2005. Bioreactor performance in anaerobic digestion of fruit and vegetable wastes (Review). Proc. Biochem., 40: 989-995. DOI: 10.1016/j.procbio.2004.03.007

Braber, K., 1995. Anaerobic digestion of municipal solid waste: A modern waste disposal option on the verge of breakthrough. Biomass Bioenergy, 9: 365-376. DOI: 10.1016/0961-9534(95)00103-4

Browne, J.D. and J.D. Murphy, 2013. Assessment of the resource associated with biomethane from food waste. Applied Energy, 104: 170-177. DOI: 10.1016/j.apenergy.2012.11.017

Chang, H.N., J.K. Cho and S.C. Park, 1995. Biochemical methane potential and solid state anaerobic digestion of Korean food wastes. Bioresource Technol., 52: 245-253. DOI: 10.1016/0960-8524(95)00031-9

CITEC, 2004. CITEC Guidelines 2004. The Design, Production and Running of High Technology Plant for the Disposal of Urban Waste. 1st Geva, Rome, Italy, ISBN-10: 8889323086, pp: 280.

Comparetti, A., C. Greco, K. Navickas and K. Venslauskas, 2012. Evaluation of potential biogas production in Sicily. Proceedings of the 11th International Scientific Conference on Engineering for Rural Development, May 24-25, Jelgava, Latvia, pp: 555-559.

Comparetti, A., P. Febo, C. Greco and S. Orlando, 2013a. Current state and future of biogas and digestate production. Bulgarian J. Agric. Sci., 19: 1-14.

Comparetti, A., P. Febo, C. Greco, S. Orlando and K. Navickas *et al*., 2013b. Sicilian potential biogas production. J. Agric. Eng., 45: 522-525. DOI: 10.4081/jae.2014.242

Corsten, M., E. Worrell, M. Rouw and A. Van Duin, 2013. The potential contribution of sustainable waste management to energy use and greenhouse gas emission reduction in the Netherlands. Resources, Conservat. Recycl., 77: 13-21. DOI: 10.1016/j.resconrec.2013.04.002

Cucchiella, F., I. D'adamo and M. Gastaldi, 2014. Strategic municipal solid waste management: A quantitative model for Italian regions. Energy Convers. Manage., 77: 709-720. DOI: 10.1016/j.enconman.2013.10.024

Dagnall, S., 1995. UK strategy for centralised anaerobic digestion. Bioresource Technol., 52: 275-280. DOI: 10.1016/0960-8524(95)00039-H

Di Maria, F., A. Sordi and C. Micale, 2012. Energy production from mechanical biological treatment and composting plants exploiting solid anaerobic digestion batch: An Italian case study. Energy Convers. Manage., 56: 112-120. DOI: 10.1016/j.enconman.2011.11.023

Dong, J., Y. Chi, D. Zou, C. Fu and Q. Huang *et al*., 2014. Energy-environment-economy assessment of waste management systems from a life cycle perspective: Model development and case study. Applied Energy, 114: 400-408. DOI: 10.1016/j.apenergy.2013.09.037

Edelmann, W., K. Schleiss and A. Joss, 2000. Ecological, energetic and economic comparison of anaerobic digestion with different competing technologies to treat biogenic wastes. Water Sci. Technol., 41: 263-273.

Eriksson, O., M. Bisaillon, M. Haraldsson and J. Sundberg, 2014. Integrated waste management as a mean to promote renewable energy. Renewable Energy, 61: 38-42. DOI: 10.1016/j.renene.2012.04.024

EU, 1999. Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste. WEEE Forum.

EU, 2002. Regulation (EC) 1774/2002 of the European Parliament and of the Council of 3 October 2002 laying down health rules concerning animal by-products not intended for human consumption. Official Journal of the European Communities.

EUCAR, 2007. Well-to-wheels analysis of future automotive fuels and power trains in the European context. EUCAR.

Fantozzi, F. and C. Buratti, 2011. Anaerobic digestion of mechanically treated OFMSW: Experimental data on biogas/methane production and residues characterization. Bioresource Technol., 102: 8885-8892. DOI: 10.1016/j.biortech.2011.06.077

Febo, P. and D. Pessina, 1995. Survey of the working condition of used tractors in Northern Italy. J. Agric. Eng. Res., 62: 193-202. DOI: 10.1006/jaer.1995.1077

Fernandez Rodriguez, J., M. Perez and L.I. Romero, 2012. Mesophilic anaerobic digestion of the organic fraction of municipal solid waste: Optimisation of the semicontinuous process. Chem. Eng. J., 194: 10-15. DOI: 10.1016/j.cej.2012.04.018

Gallert, C. and J. Winter, 1997. Mesophilic and thermophilic anaerobic digestion of source-sorted organic wastes: Effect of ammonia on glucose degradation and methane production. Applied Microbiol. Biotechnol., 48: 405-410. DOI: 10.1007/s002530051071

Gallert, C., A. Henning and J. Winter, 2003. Scale-up of anaerobic digestion of the biowaste fraction from domestic wastes. Water Res., 37: 1433-1441. DOI: 10.1016/S0043-1354(02)00537-7

Grillone, G., G. Baiamonte and F. D'Asaro, 2014. Empirical determination of the average annual runoff coefficient in the Mediterranean area. Am. J. Applied Sci., 11: 89-95. DOI: 10.3844/ajassp.2014.89.95

Habib, K., J.H. Schmidt and P. Christensen, 2013. A historical perspective of global warming potential from municipal solid waste management. Waste Manage., 33: 1926-1933. DOI: 10.1016/j.wasman.2013.04.016

Hamzawi, N., K.J. Kennedy and D.D. Mc Lean, 1999. Review of applications of high solids anaerobic digestion to solid waste management. J. Solid Waste Technol. Manage., 26: 119-132.

Hartmann, H. and B.K. Ahring, 2003. Phthalic acid esters found in municipal organic waste: Enhanced anaerobic degradation under hyper-thermophilic conditions. Water Sci. Technol., 48: 175-183.

He, R., D. Shen, J. Wang, Y. He and Y. Zhu, 2005. Biological degradation of MSW in a methanogenic reactor using treated leachate recirculation. Proc. Biochem., 40: 3660-3666. DOI: 10.1016/j.procbio.2005.02.022

Holm-Nielsen, J.B., N. Halberg, S. Hutingford and T. Al Seadi, 1997. Joint biogas plant agricultural advantages-circulation of N, P and K. Danish Energy Agency, Copenhagen, Denmark.

Holm-Nielsen, J.B., T. Al Seadi and P. Oleskowicz-Popiel, 2009. The future of anaerobic digestion and biogas utilization. Bioresource Technol., 100: 5478-5484. DOI: 10.1016/j.biortech.2008.12.046

Hoornweg, D. and P. Bhada-Tata, 2012. What a Waste: A Global Review of Solid Waste Management. World Bank, Washington, USA.

Kathiravale, S. and M.N. Yunus, 2008. Waste to wealth. Asian Eur. J., 6: 359-371. DOI: 10.1007/s10308-008-0179-x

Kim, M., Y.H. Ahn and R.E. Speece, 2002. Comparative process stability and efficiency of anaerobic digestion; mesophilic Vs. thermophilic. Water Res., 36: 4369-4385. DOI: 10.1016/S0043-1354(02)00147-1

Kim, S.W., J.Y. Park, J.K. Kim, J.H. Cho and Y.N. Chun *et al*., 2000. Development of a modified three-stage methane production process using food wastes. Applied Biochem. Biotechnol., 86: 731-741. DOI: 10.1007/978-1-4612-1392-5_56

Krzystek, L., S. Ledakowicz, H.J. Kahle and K. Kaczorek, 2001. Degradation of household biowaste in reactors. J. Biotechnol., 92: 103-112. DOI: 10.1016/S0168-1656(01)00352-2

Lema, J.M. and F. Omil, 2001. Anaerobic treatment: A key technology for a sustainable management of wastes in Europe. Water Sci. Technol., 44: 133-140.

Liamsanguan, C. and S.H. Gheewala, 2008. The holistic impact of integrated solid waste management on greenhouse gas emissions in Phuket. J. Clean Prod, 16: 865-871. DOI: 10.1016/j.jclepro.2007.12.008

Lissens, G., P. Vandevivere, L. De Baere, E.M. Biey and W. Verstrae, 2001. Solid waste digestors: Process performance and practice for municipal solid waste digestion. Water Sci. Technol., 44: 91-102. PMID: 11730142

Mace, S., D. Bolzonella, F. Cecchi and J. Mata-Alvarez, 2003. Comparison of the biodegradability of the grey fraction of municipal solid waste of Barcelona in mesophilic and thermophilic conditions. Water Sci. Technol., 48: 21-28. PMID: 14531418

Mata-Alvarez, J., 2003. Biomethanization of the Organic Fraction of Municipal Solid Wastes. 1st Edn., IWA Publishing, London, UK, ISBN-10: 1900222140, pp: 323.

Mata-Alvarez, J., P. Llabres, F. Cecchi and P. Pavan, 1992. Anaerobic digestion of the Barcelona central market organic wastes: Experimental study. Bioresource Technol., 39: 39-48. DOI: 10.1016/0960-8524(92)90054-2

McDougall, F., P. White, M. Frank and P. Handle, 2001. Integrated Solid Waste Management: A Life Cycle Inventory. 2nd Edn., Blackwell Publishing, Cornwall, UK, ISBN-10: 978-0-632-05889-1, pp: 544.

Menikpura, S.N.M., J. Sang-Arun and M. Bengtsson, 2013. Integrated solid waste management: An approach for enhancing climate co-benefits through resource recovery. J. Cleaner Product., 58: 34-42. DOI: 10.1016/j.jclepro.2013.03.012

Menikpura, S.N.M., S.H. Gheewala and S. Bonnet, 2012. Framework for life cycle sustainability assessment of municipal solid waste management systems with an application to a case study in Thailand. Waste Manage. Res., 30: 708-719. DOI: 10.1177/0734242X12444896

MAFF, 1986. Profitable Use of Farm Manures. Ministry of Agriculture, Fisheries and Food, London, UK.

Navickas, K., V. Zuperka and R. Janusauskas, 2003. Energy input for cultivation and preparation of biomass for biogas production. LZUI instituto ir LZU universiteto mokslo darbai/LZUU, 35: 109-116.

Nielsen, L.H., K. Hjort-Gregersen, P. Thygesen and J. Christensen, 2002. Samfundsokonomiske analyser af biogasfaellesanlaeg. Rapport 136. Fodevareokonomisk Institut, Copenhagen, Denmark.

Novarino, D. and M.C. Zanetti, 2012. Anaerobic digestion of extruded OFMSW. Bioresource Technol., 104: 44-50. DOI: 10.1016/j.biortech.2011.10.001

O'Keefe, D.M. and D.P. Chynoweth, 2000. Influence of the separation, leachate recycle and aeration on treatment of municipal solid waste in simulated landfill cells. Bioresource Technol., 72: 55-66. DOI: 10.1016/S0960-8524(99)00089-9

OALL, 2011. Ecomafia 2011. Le storie e i numeri della criminalità ambientale. 1st Edn., Edizioni Ambiente, Milano, ISBN-10: 8866270040, pp: 400.

Pavan, P., P. Battistoni, J. Mata-Alvarez and F. Cecchi, 2000. Performance of thermophilic semi-dry anaerobic digestion process changing the feed biodegradability. Water Sci. Technol., 41: 75-81.

Persson, M., Jösson O. and A. Wellinger, 2006. Biogas upgrading to vehicle fuel standards and grid injection. International Energy Agency-Bioenergy. refman.et-model.com/publications/88

Pognani, M., G. D'imporzano, B. Scaglia and F. Adani, 2009. Substituting energy crops with organic fraction of municipal solid waste for biogas production at farm level: A full-scale plant study. Proc. Biochem., 44: 817-821. DOI: 10.1016/j.procbio.2009.03.014

Pognani, M., R. Barrena, X. Font and A. Sanchez, 2012. A complete mass balance of a complex combined anaerobic/aerobic municipal source-separated waste treatment plant. Waste Manage., 32: 799-805. DOI: 10.1016/j.wasman.2011.12.018

Rao, M.S. and S.P. Singh, 2004. Bioenergy conversion studies of organic fraction of MSW: Kinetic studies and gas yield-organic loading relationships for process optimization. Bioresource Technol., 95: 173-185. DOI: 10.1016/j.biortech.2004.02.013

Rimaitytė, I., G. Denafas, D. Martuzevicius and A. Kavaliauskas, 2010. Energy and environmental indicators of municipal solid waste incineration: Toward selection of an optimal waste management system. Polish J. Environ. Studies, 19: 989-998.

Rivard, C.J., M.E. Himmel, T.B. Vinzant, W.S. Adney and C.E. Wyman *et al*., 1989. Development of a novel laboratory scale high solids reactor for anaerobic digestion of processed municipal solid wastes for the production of methane. Applied Biochem. Biotechnol., 20: 461-478. DOI: 10.1007/BF02936503

Rivard, C.J., T.B. Vinzant, W.S. Adney, K. Grohmann and M.E. Himmel, 1990. Anaerobic digestibility of two processed municipality-solid-waste materials. Biomass, 23: 201-214. DOI: 10.1016/0144-4565(90)90059-S

Saint-Joly, C., S. Desbois and J.P. Lotti, 2000. Determinant impact of waste collection and composition on anaerobic digestion performance: Industrial results. Water Sci. Technol., 41: 291-297.

Sakai, S., S.E. Sawell, A.J. Chandler, T.T. Eighmy and D.S. Kosson *et al*., 1996. World trends in municipal solid waste management. Waste Manage., 16: 341-350. DOI: 10.1016/S0956-053X(96)00106-7

Sicilian Region, 2010. Management plan of Municipal Solid Waste. Department of Water and Wastes. Palermo, Italy.

Sonesson, U., A. Bjöklund, M. Carlsson and M. Dalemo, 2000. Environmental and economic analysis of management systems for biodegradable waste. Resources, Conservat. Recycl., 28: 29-53. DOI: 10.1016/S0921-3449(99)00029-4

Stretton-Maycock, D. and G. Merrington, 2009. The Use and Application to Land of MBT Compost-like Output-Review of Current European Practice in Relation to Environmental Protection. 1st Edn., Environment Agency United Kingdom, ISBN-10: 1844329739, pp: 38.

Tabata, T., T. Hishinuma, T. Ihara and Y. Genchi, 2011. Life cycle assessment of integrated municipal solid waste management systems, taking account of climate change and landfill shortage trade-off problems. Waste Manage. Res., 29: 423-432. DOI: 10.1177/0734242X10379493

Tchobanoglous, G., F.L. Burton and H.D. Stensel, 2002. Wastewater Engineering: Treatment and Reuse. 4th Edn., McGraw-Hill Science/Engineering/Math, ISBN-10: 0070418780, pp: 1848.

Tchobanoglous, G., T. Hilary and S.A. Vigil, 1993. Integrated Solid Waste Management: Engineering Principles and Management Issues. 2nd Edn., McGraw-Hill, New York, ISBN-10: 0070632375, pp: 978.

Themelis, N.J. and S. Verma, 2004. Anaerobic Digestion of Organic Waste in MSW. Waste Management World, 20-24: 20-24.

Thorneloe, S. and J. Pacey, 1994. Landfill gas utilization: Database of North American Projects. Proceedings of the 17th Annual Landfill Gas Symposium, Mar. 22-24, SWANA, Silver Spring, USA, pp: 197-208.

Tilche, A. and F. Malaspina, 1998. Biogas production in Europe: An overview. Proceedings of the 10th European Conference on Biomass for Energy and Industry, Jun. 8-11, C.A.R.M.E.N., Wurzburg, Germany.

Tudisca, S., A.M. Di Trapani, F. Sgroi, R. Testa and R. Squatrito, 2013. Economic analysis of PV systems on buildings in Sicilian farms. Renewable Sustainable Energy Rev., 28: 691-701. DOI: 10.1016/j.rser.2013.08.035

Ward, A.J., P.J. Hobbs, P.J. Holliman and D.L. Jones, 2008. Optimisation of the anaerobic digestion of agricultural resources. Bioresource Technol., 99: 7928-7940. DOI: 10.1016/j.biortech.2008.02.044