Biomethanation of food waste in farm scale systems

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Abstract

Purpose: Nowadays approximately the 30-40% of food products destined for human consumption are transformed into wastes and landfilled. Landfilling of food waste results in the wastage of a substrate, pollution of ground and underground waters and releases of greenhouse gases into the environment. In this work we assessed and compared the environmental impact of three waste management scenarios for the organic fraction of the municipal solid waste (OfMSW).

Methods: The redirection of the organic fraction of the municipal solid wastes is a requirement of current legislation in order to minimize the environmental impact of human activity, unfortunately through life cycle assessment the merits of this redirection cannot be reproduced either for the application of anaerobic digestion or composting. Anaerobic digestion is a usual organic waste redirection method offering the opportunity for the recovery of biogas which can be used as a fuel gas for energy generation. In order to improve the environmental impact scoring of the redirection systems we investigated both the effect of the addition of the organic municipal wastes into farm digesters as well as the construction of new digesters for the management of the organic wastes as single substrates.

Results: The results revealed that the valorization of the organic wastes into farm digesters is a sustainable method offering significant environmental merits compared to scores calculated for the case of the construction of new specialized digesters.

Conclusion: Co-digestion can be a solution for both the low volume of biogas recovered by the manure digesters as well as to the digestion of the unbalanced organic wastes streams.

Keywords: anaerobic digestion, co-digestion, food waste, farm scale digestion systems, waste management

1 Introduction

Production of biodegradable municipal wastes is increasing worldwide, while the scientific community and waste managers develop technologies and strategies for the utilization or valorization of these streams. According to the European Union Directives 1999/31/EC & 2008/98/EC as well as the 20-20-20 strategy, European States are obliged to minimize the disposal of biodegradable wastes to 35% of that produced in 1995 by 2016, as well as to enforce 50% reuse or recycling of household wastes by 2020. The 20/20/20 strategy requires that 20% of the total energy consumed within the EC must derive from renewable sources, while the 2008/98/EC Directive necessitates the adoption of waste management plans and waste prevention strategies by Member States.

According to Bakas, Milios [1] the MSW stream in Greece is estimated at 6 million tons/y that contain approximately 40% putrescibles a stream likely to be managed with the application of biological valorization processes. However, for the successful application of biological treatment methods to this waste stream, it is essential the integration of the valorization systems under a common management strategy that will begin with a source separation scheme for all reusable, recyclable, and utilizable matter and conclude at the landfill for the left overs.

Although the volume of municipal waste increases, the currently applied management methods (landfilling, incineration) raising significant concerns due to their inefficiency to treat the OfMSW. Furthermore, the presence of organic matter in the waste streams are responsible for leachate formation in landfills, insulting odors production, pest reproduction [2], low calorific value and significant air pollutant releases when these wastes are incinerated. As a consequence the redirection and utilization of the OfMSW will improve the quality and efficiency of other down the line processes in a win win process.

The alternative treatment methods that can be applied to the OfMSW are mainly these utilizing microorganisms and are divided into two basic categories: 1) aerobic, which leads to the production of a stabilized organic fertilizer and gaseous releases (CO_2, NH_4) and 2) anaerobic digestion which leads to the production of biogas (CH_4, CO_2, H_2S) and a relatively stabilized liquid residue, which requires a further aerobic treatment stage in order to be considered as compost [3],[4],[5]. Anaerobic digestion is a waste management method attracting great interest from the scientific community due to its ability to treat high solids waste while producing a renewable fuel in the form of biogas which is containing 55-70% methane. The generated gas can be utilized for energy generation n site reducing in this way the pressure of human activities on natural resources and the environment, while providing a tool to European States for meeting the renewable energy and landfilling redirection targets. Apart from the renewable fuel, the AD process is generating the digestate that contains most of the nutrients and micronutrients entering the process and is an effluent that can be used as an excellent, in most cases, organic and slow release fertilizer.

A number of countries in order to stimulate the treatment and recovery of organic wastes, have establish economic incentives in the form of feed in tariffs for electric energy generated through the management of waste streams. Greece for instance is offering 200-220 Euros/MWh_{el} generated from anaerobic digestion with the application of wastes as substrates (National Law N.3851/2010). The management of the OfMSW based on the anaerobic digestion is a proven technology applied in industrial facilities both in wet and dry systems, with the methane production reported fluctuating between 210 and 530 $mLCH_4/gVS_{added}$ [6,7]. On the other hand many digesters treating the OfMSW as single substrate, presenting low stability due to acidification, high sodium content, lack of essential trace elements and high ammonia levels [8,6,9] rendering pretreatment or addition of required elements necessary something that increasing complexity and operational costs. In our previous work Zarkadas et al. [10] we showed that the addition of food waste to manure digesters is desirable for up to a loading rate of 6.2 $kgVSm^3$-d. Under these operational conditions the system reduces volatile solids (VS) by 72% with specific methane production improving by 86% when compared to the cattle manure monodigestion. Furthermore a fourfold improvement in cash flows must be expected only through the addition of food waste into the anaerobic digestion system and without taking into account the possible gate fees and the improved quality of the generated digestate. This work aims on assessing the biomethane potential, the economics of the systems and the overall life cycle of the organic municipal waste as substrate to AD systems.

2 Material and methods

2.1 Batch digestion

For this work 118mL glass bottles were used as bioreactors. During the preparation of the batches, the vials were filled with the inoculum and substrate, flashed with N_2 in order to achieve anaerobic condition and incubated in a temperature controlled cabinet under thermophilic conditions. For these experiments the inoculum to substrate ratio was set to 1.5 as this has been shown as safe when assessing similar readily acidified substrate as is the case of the OfMSW. The cow manures utilized were collected from a local farm, while the OfMSW were collected from a canteen. The OfMSW had a total solid concentration of 33.9% a high TNK concentration of 7.4g/L and a low pH equal to 5.1. On the other hand the cattle manure presented a total solid concentration of 6.7 and a neutral pH of 7.3. The OfMSW addition ratios assessed were the 10, 20 and 30% with the last value being nearly the 80% when considering the VS addition.

2.1.1 Analytical methods

Total solids, volatile solids and pH were analyzed according to the Standard Methods (APHA, 1989). For the bio methane production the generated biogas scrubbed in a 2N NaOH solution and the recovered gas measured in an inverted 250 mL volumetric cylinder operating according to the water displacement principle. The concentration of methane validated with the application of a Shimadgu GC2014 coupled to a thermal conductivity detector. The Total Kjeldahl Nitrogen was analyzed with a HACH Digesdahl Digestion Apparatus and the method 8075 while a Shimadzu GC 17A coupled to a flame ionization detector were used. Total organic carbon analyzed with a Shimadzu TOC-VCPH analyzer coupled to a solid state combustion unit SSM-5000A. All the results are given have been converted into standard temperature and pressure conditions.

2.2 LCA methodology

Life Cycle Assessment (LCA) is an internationally recognized environmental assessment tool that can be employed for comparing "assessing" different options based on "known", measured, calculated or expected data "assumed". LCA methodologies provide the tool for quantifying the material, energy and the impacts i.e. wastes, that different products or services have during their life cycle. Furthermore, during the LCA "hot spot" areas of significant importance can be identified and provide the primary target of a remediation stage, where with balanced inputs-outputs the higher gains can be achieved [11]. On the other hand and based on the targeted operation by the LCA the outcome of the system (i.e the boundaries) can be extended to include not only the direct impacts and gains, but also the environmental gains due to the avoided impacts of the product or service that never realized "avoided".

The uncertainty of the LCA is always high especially when the outcome is based on requirements and parameters that are directly influenced by socioeconomic activity, including but not limited to efficiency and effectiveness of different processes, community participation, technology development, community size, waste production and GDP.

A number of researchers have utilized LCA on a quest to identify the most appropriate technology and/or integrated method for the waste management targeting different countries, cities or towns [12-14], municipal solid waste management systems [15,16] and effluent management technologies [17]. As LCA can provide results applicable to a specific location it is also extremely sensitive to the introduced data which must be specially developed for the analyzed area or process. Variances between different studies including boundaries, targeted process, environmental conditions, economic activity, and methodology can affect the results and bias the results towards different outcomes.

In this study, the LCA analysis was carried out comparing three alternative scenarios. The evaluation was conducted according to ISO 14040 principle and guidelines [18]. According to ISO 14040, the applied LCA compises for stages: goal and scope defintiion, life cycle inventory, life cycle impact analysis and interpretations of the result.

2.2.1 Goal and definition

During Life Cycle Assessments is very important to identify the functional unit that will be used, and based on which, the inputs, outputs and the results of the analysis will be expressed in quantitative terms (table 1/fig.1). In the current LCA the functional unit (FU) is one ton of mixed wastes of both bins (green and blue). The mixed waste composition will be assumed as is the average value per waste stream calculated based on published data of the three available studies that conducted in Greece after year 2000.

The system boundaries consisted of the collection of MSW waste form the urban areas including the waste transport as well as the waste treatment facilities. Also, LCA took into account the material stream and energy flow of the recycling network and it was not limited only in the landfilling of the residual materials.

Table 1. Greek municipal solid waste composition

	39624/2209/E103/2009 , J.M.D.J [19]	YPEKA [20]	Papachristou et al. [21]	Average and assumed composition of wastes
Putrescible (%)	47	40	26.3	37.9
Paper (%)	20	29	25.9	25
Plastics (%)	8.5	14	19.7	14
Metals (%)	4.5	3	3.4	3.6
Glass (%)	4.5	3	3.7	3.7

Wood – green wastes	4	6	-	5[1]
Other types or mixed wastes (%)	11.5	9	21.3	10.9[1]

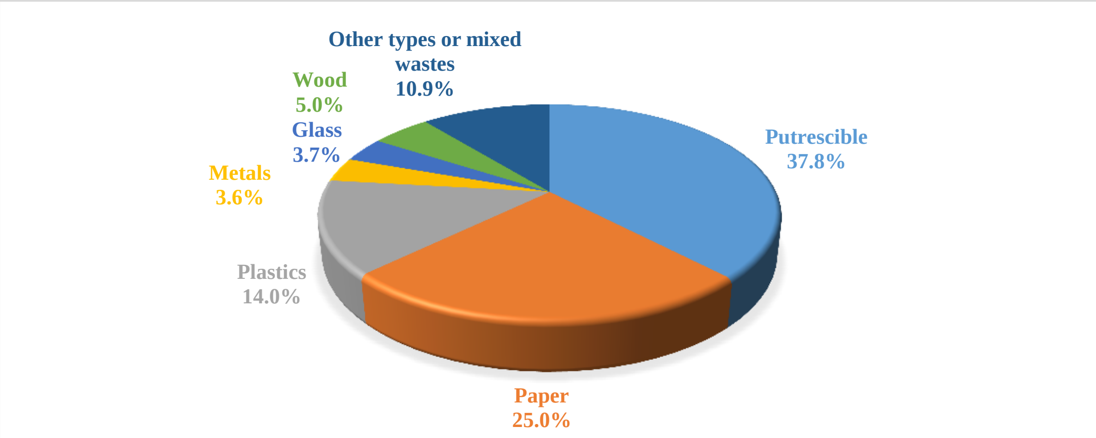

Figure 1. Municipal solid waste generation for Greece in percentages of the total volume (i.e. 6 million tons)

2.2.2 Life cycle inventory

The LCA analysis was conducted using the SimaPro 7.1 [22]. Hence, the software database was adjusted to the condition in Greece and also the digestion treatment characteristics were enhanced using the laboratory results. Additionally, the selection of the data quality indicators such as time, technology and geography were done using the DQI (Data Quality Indicator) that was provided by SimaPro.

The waste transportation system was divided to transportation from the collection point to refuse disposal station and the transportation to the waste treatment. Additionally, the recycling facilities distance from the refuse disposal station were assumed 40 km. The examined scenarios assumed that the collection points consisted of two sources: a biodegradable bin and a recycling bin. The efficiency at the different points of the systems were used for the analysis were:

- Source separation of recyclable and biodegradable wastes in the urban areas 80%,
- Losses in the refuse disposal station 10%
- Separation of recycling material in the recycling industry 90%

2.2.3 Life cycle impact assessment

CML 2 baseline 2000 was used for the LCA and investigated indices were the abiotic depletation, the acidification, the eutrophication, the Global warming, the human toxicity, the fresh water aquatic. ecotoxicity, the marine aquatic ecotoxicity and the photochemical oxidation.

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2.3 Scenarios

2.3.1 Scenario 1.

This scenario is considered our baseline system which is actually what is taking place in Greece. This scenario is related to the collection and transportation of the wastes into the landfill with the consumption of oil fuel. The analysis includes parameters including: construction, transportation, landfill machinery, leachate treatment, biogas and other airborne releases.

[1] *Due to the fact that data related to green wastes is not available in these studies, an assumption will be used that 3% of the total wastes is composed of green wastes. This 3% will be deduced from the "other types of mixed waste category" and added to the "wood category".*

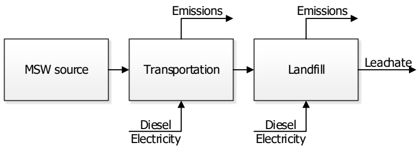

Figure 2 Flow chart for scenario 1.

2.3.2 Scenario 2

Landfilling with application of anaerobic digestion for treating the putrescible. In this scenario the biogas will be polished and used in a CHP where energy in the form of electricity will be recovered. The generated heat will be used onsite, for heating the digester, while the rest will be dumped in to the atmosphere. In this scenario the analysis will be based on the background that the digester will be constructed only for the management of the OfMSW and it will be operated with only this substrate.

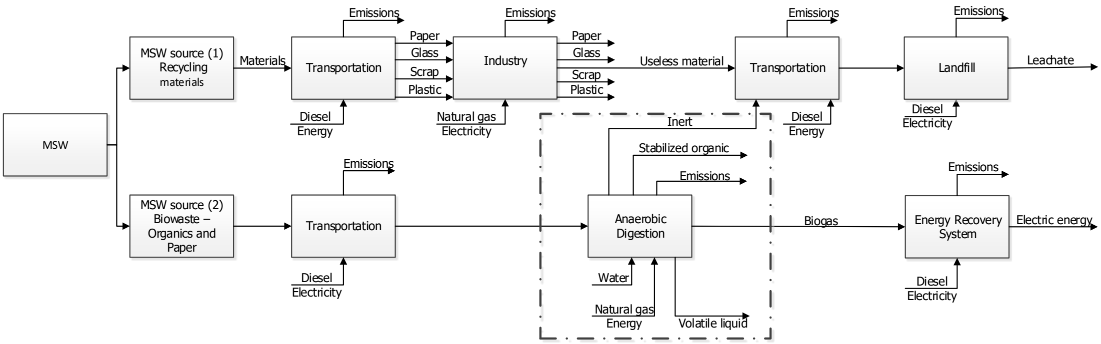

Figure 3. Flow diagram of scenario 2 and 3. The difference of the two scenarios are related to the requirement for the construction of the new digesters or the valorization of the wastes into farm scale systems

2.3.3 Scenario 3

The third scenario is very similar to scenario 2, however the digesters that will be utilized will be farm scale systems that will increase their loading rates and when required will improve their effectivity by increasing their operating temperature into the thermophilic range. Thermophilic digestion (50-55^{o}C) it is known to offer significantly higher throughputs compared to mesophilic systems [23].

3 Results and discussion

3.1 Biomethane potential

In figure 4 it is presented the biomethane production of the different mixtures of OfMSW and cattle manure, as it is shown the specific production fluctuated between 272 and 408 mL CH_4-gVS, which is at least 50mLCH higher by the value offered by the monodigestion of cattle manure. During the process no inhibition was identified while the volatile fatty acid concentrations, a significant indicator of the process, reached concentrations of up to 1.8g/L and only during the initial stage of the process, followed by their subsequent reduction until their complete bioconversion into biogas.

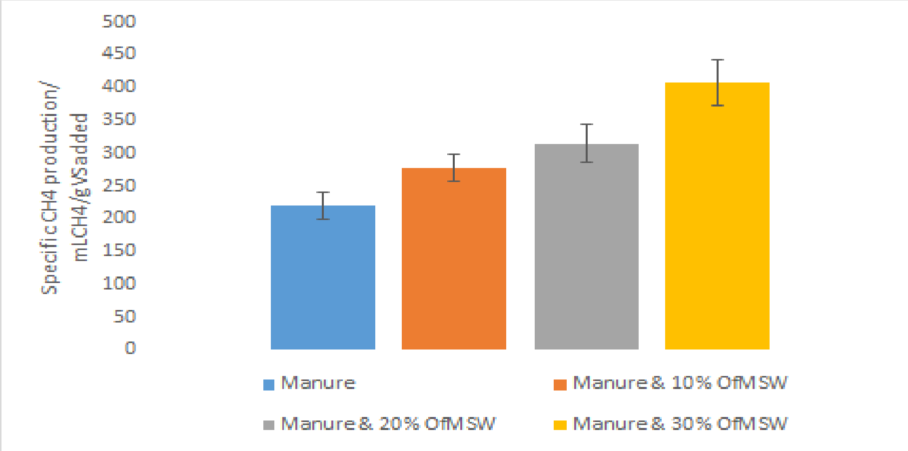

Fig. 4 Specific methane production for the different substrates and substrate mixtures

Similar biomethane potentials for the OfMSW were also reported by [24,25] while both researchers identified limitations related to the biomethanation of the OfMSW either due to the lack of essential micronutrients or high ammonia concentrations. Obviously, the OfMSW is a low C/N substrate and its valorization under aerobic or anaerobic conditions is very challenging either due to the toxicity of ammonia toward the anaerobic microflora, or the loss of ammonia, an essential plant nutrient into the atmosphere. Another importance merit of the adition of the OfMSW into farm scale digesters derive by its high VS content which can tremendously improve the volumetric biomethane production without requiring the reduction of the HRT lower than 20 days, which is unfortunately impossible in the case of the manure as single substrate.

3.2 Life Circle Assessment

Recently life cycle analysis utilized for the evaluation and comparison of the waste management systems applied on the organic fraction of the municipal streams in the borders of Germany and Denmark [26]. The difference between the two countries is that the German area utilizes composting and anaerobic digestion, while the Danish area incinerates the generated organic wastes. The results of this study revealed that the Danish area performs better in 10 out of the 14 impact categories. While this is strange a number of other studies also revealed that the comparison of anaerobic digestion and incineration through LCA cannot yield a winner and offering an unclear result [27,28]. In a number of indicators, as is the case of eutrophication, the application of digestate on land can give rise to leachate formation and as a consequence to eutrophication of surface water bodies. On the other hand the application of digestate minimizing the utilization of chemical fertilizers offering energy consumption reduction. Furthermore, the low loading rates applied on farm digestion systems as a result of the low solid concentration of manure and the high hydraulic retention time required by anaerobic systems can reduce both the environmental scoring of these systems as well as the financial indicators. Through the utilization of the OfMSW as substrate to AD systems the HRT of the digesters can sustained relatively high >20 days while at the same time the OLR can be increased to levels higher than 5kgVSm^3-d where significant volumes of biogas can be recovered.

The results of the LCA indicate that the described scenario of the sanitary landfill has higher environmental impact. Obviously the loss of substrates and recyclables to the landfill and the generated leachates and greenhouse gases have significant impact both to the environmental quality as well as to the natural resources. In particular, scenarios 2 and 3 consume less abiotic matter at levels exceeding the 30% with the best scores to be presented for the fresh water and marine aquatic ecotoxicity, with reduction of up to 95% compared to the score for scenario 1. On the other hand, acidification is a major concern for all the scenario with the highest score to be observed for scenario 1. Additionally, the global warming score of landfilling appears much higher compared to the other two scenarios. This fact is related to the significant amount of raw methane emissions that are originated by the uncontrolled bio-waste digestion which inevitable disperse into the environment. After waste deposition into landfill, anaerobic digestion microorganisms decompose the organic matter into greenhouse gases. While in a number of instances the collection of these gases can offer environmental impact reduction, the economics of the systems are not favorable due to the low activity and the small life span of the overall system. In contrast, the MSW managements based on recycling as well as recycling and anaerobic digestion have a considerable low global warming effect. Moreover the recycling treatments are significantly favorable to the ozone layer depletion among all management methods. A significant and not intuitive result is the fact that in case of scenario that include biodegradable methods the pollution of the groundwater is lower than the sanitary landfill. It has to be noted using anaerobic methods that contain leachate waste treatments, the reduction in the marine and fresh water ecotoxicity can be exceed the 80% comparatively to the landfill. Landfilling has also the highest photochemical potential among all other management options due to the large volumes of untreated air releases.

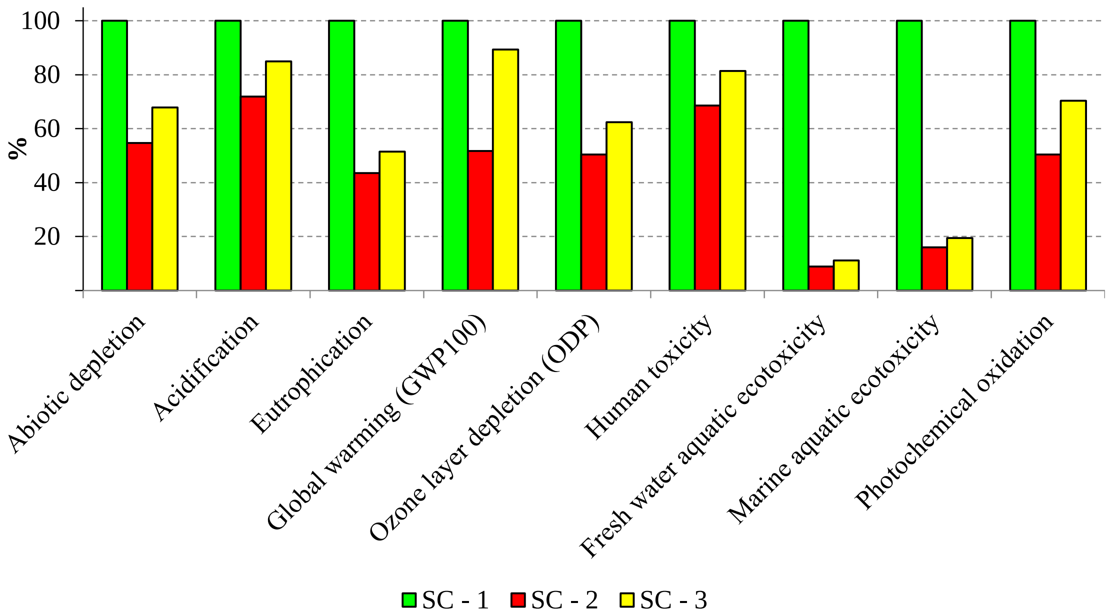

Figure 5. Life cycle analysis results. Comparison of indicators based on method: CML 2 baseline 2000

Compering the scenario 2 and 3 it is clear that the utilization of available digesters it is offering significant environmental merits. The calculated environmental indicators for scenario 2 presenting scores higher by up to 40% compared to these calculated for the construction of complete new facilities. It is observed that in case of utilizing the existence infrastructures the environmental indicator of the greenhouse effect is only the 42% compared to the one calculated for the construction of new facilities.

Franchetti [29] studied four different scenarios for the management of food wastes into the area of Northern Ohio, USA and concluded that the anaerobic digestion can significantly reduce the environmental foot print of food waste management. Even though Franchetti studied the LCA of high tech high cost digestion systems, including two stage digestion, ultrasound pretreatment and addition of trace elements into the digesters.

4. Methane production - cash flow analysis

Apart from the LCA, the results of the present research can be used for the generation of an economic scenario for a TAD system based on a single 3.000 m^3 CSTR which is treating CM with a daily influent stream of 140 m^3 (HRT ~21-d) of wastes. For this scenario the border is considered the screw feeder of the system and no consideration of collection, possible separation or transportation is taken into account due to the fact that the local communities are already responsible to collect, pretreat and redirect the organic fraction of their waste. The daily output based on electric energy, with an energy content of methane of 9.77 kWh and a conversion efficiency of 33%, for this unit is approximately 5.400 kWh of electric power (i.e. 1.200 €-d based on the 220 € per MWh feed-in tariff offered at the moment in Greece for digesters operating mostly on wastes (Greek Law N.3851/2010)). However, by altering the feeding mixture with the introduction of 10 and 20% FW the daily output of the system will be: 10.700 kWh (i.e. 2.350 €-d) and 19.700 kWh (i.e. 4.350 €-d) respectively, which is an improvement that can be reached by only slightly increasing, due to the size reduction and pasteurisation requirements for the FWs, the operational costs of the treatment unit[30].

5. Conclusion

The life cycle impact of collection and different waste disposal strategies such as Landfilling, Recycling and Biological methods was performed by means of a multi-method and multi-scale approach. The results of the assessment based on selected impact indicators lead to the conclusions that the combination of biological and mechanical methods have the lower abiotic matter, acidification potential, greenhouse gas effect, ozone depletion and photochemical oxidation among the examined waste management systems. These results reveal and underline the need of exploring further the biological treatment of waste in Greece. Moreover the study has shown that landfilling is the worst waste management strategy and that other options for waste treatment coupled material recovery would as well as biological methods result in potential and remarkable benefits such as reduction of greenhouse emissions.

Additionally, the optimization on the process as well as on the logistics of the input waste stream in the existence biological treatment infrastructures could ameliorate more the environmental profits.

6. References

1. Bakas, I., Milios, L.: Municipal waste management in Greece. European Environmental Agency (2012).

2. Al-Yaqout, A.F., Koushki, P.A., Hamoda, M.F.: Public opinion and siting solid waste landfills in Kuwait. Resources, Conservation and Recycling **35**(4), 215-227 (2002). doi:http://dx.doi.org/10.1016/S0921-3449(01)00111-2

3. Benemann, J.: Hydrogen biotechnology: Progress and prospects. Nature Biotechnology **14**(9), 1101-1103 (1996).

4. Angelidaki, I., Ellegaard, L.: *Codigestion of manure and organic wastes in centralized biogas plants: Status and future trends*. Applied Biochemistry and Biotechnology - Part A Enzyme Engineering and Biotechnology **109**(1-3), 95-105 (2003).

5. Verstraete, W., Vandevivere, P.: New and Broader Applications of Anaerobic Digestion. Environmental Science and Technology (1999).

6. Yong, Z., Dong, Y., Zhang, X., Tan, T.: Anaerobic co-digestion of food waste and straw for biogas production. Renewable Energy **78**, 527-530 (2015). doi:http://dx.doi.org/10.1016/j.renene.2015.01.033

7. Koch, K., Helmreich, B., Drewes, J.E.: Co-digestion of food waste in municipal wastewater treatment plants: Effect of different mixtures on methane yield and hydrolysis rate constant. Applied Energy **137**(0), 250-255 (2015). doi:http://dx.doi.org/10.1016/j.apenergy.2014.10.025

8. Nie, H., Jacobi, H.F., Strach, K., Xu, C., Zhou, H., Liebetrau, J.: Mono-fermentation of chicken manure: Ammonia inhibition and recirculation of the digestate. Bioresource Technology **178**, 238-246 (2015). doi:http://dx.doi.org/10.1016/j.biortech.2014.09.029

9. Haider, M.R., Zeshan, Yousaf, S., Malik, R.N., Visvanathan, C.: Effect of mixing ratio of food waste and rice husk co-digestion and substrate to inoculum ratio on biogas production. Bioresource Technology **190**, 451-457 (2015). doi:http://dx.doi.org/10.1016/j.biortech.2015.02.105

10. Zarkadas, I.S., Sofikiti, A.S., Voudrias, E.A., Pilidis, G.A.: Thermophilic anaerobic digestion of pasteurised food wastes and dairy cattle manure in batch and large volume laboratory digesters: Focussing on mixing ratios. Renewable Energy **80**(0), 432-440 (2015). doi:http://dx.doi.org/10.1016/j.renene.2015.02.015

11. Berglund, M., Börjesson, P.: Assessment of energy performance in the life-cycle of biogas production. Biomass and Bioenergy **30**(3), 254-266 (2006). doi:http://dx.doi.org/10.1016/j.biombioe.2005.11.011

12. Evangelisti, S., Lettieri, P., Borello, D., Clift, R.: Life cycle assessment of energy from waste via anaerobic digestion: A UK case study. Waste Management **34**(1), 226-237 (2014). doi:http://dx.doi.org/10.1016/j.wasman.2013.09.013

13. Turconi, R., Butera, S., Boldrin, A., Grosso, M., Rigamonti, L., Astrup, T.: Life cycle assessment of waste incineration in Denmark and Italy using two LCA models. Waste management & research : the journal of the International Solid Wastes and Public Cleansing Association, ISWA **29**(10 Suppl), 78-90 (2011). doi:10.1177/0734242x11417489

14. Bovea, M.D., Ibáñez-Forés, V., Gallardo, A., Colomer-Mendoza, F.J.: Environmental assessment of alternative municipal solid waste management strategies. A Spanish case study. Waste Management **30**(11), 2383-2395 (2010). doi:http://dx.doi.org/10.1016/j.wasman.2010.03.001

15. Allegrini, E., Vadenbo, C., Boldrin, A., Astrup, T.F.: Life cycle assessment of resource recovery from municipal solid waste incineration bottom ash. Journal of environmental management **151**, 132-143 (2015). doi:http://dx.doi.org/10.1016/j.jenvman.2014.11.032

16. Toniolo, S., Mazzi, A., Garato, V.G., Aguiari, F., Scipioni, A.: Assessing the "design paradox" with life cycle assessment: A case study of a municipal solid waste incineration plant. Resources, Conservation and Recycling **91**, 109-116 (2014). doi:http://dx.doi.org/10.1016/j.resconrec.2014.08.001

17. Börjesson, P., Berglund, M.: Environmental systems analysis of biogas systems—Part II: The environmental impact of replacing various reference systems. Biomass and Bioenergy **31**(5), 326-344 (2007). doi:http://dx.doi.org/10.1016/j.biombioe.2007.01.004

18. Arvanitoyannis, I.S.: ISO 14040: life cycle assessment (LCA)–principles and guidelines. Waste management for the food industries, 97-132 (2008).

19. 39624/2209/E103/2009, J.M.D.J.: "Measures, conditions and restrictions about the management of waste from extractive industries, in compliance with the provisions of Directive 2006/21/ EC. (2010).

20. YPEKA, H.M.o.t.E., Energy and Climate Change: National Waste Management Plan. http://www.opengov.gr/minenv/?p=6644 (2015).

21. Papachristou, E., Hadjianghelou, H., Darakas, E., Alivanis, K., Belou, A., Ioannidou, D., Paraskevopoulou, E., Poulios, K., Koukourikou, A., Kosmidou, N., Sortikos, K.: Perspectives for integrated municipal solid waste management in Thessaloniki, Greece. Waste management (New York, N.Y.) **29**(3), 1158-1162 (2009). doi:10.1016/j.wasman.2008.04.015

22. Goedkoop, M., Oele, M., de Schryver, A., Vieira, M.: SimaPro database manual methods library. PRé Consultants, The Netherlands (2008).

23. Zarkadas, I.S., Pilidis, G.A.: Anaerobic Co-Digestion of table olive debittering: washing Effluent, cattle manure and pig manure in batch and high volume laboratory anaerobic digesters: Effect of temperature. Bioresource Technology **102**(8), 4995-5003 (2011). doi:http://dx.doi.org/10.1016/j.biortech.2011.01.065

24. Hartmann, H., Ahring, B.K.: Anaerobic digestion of the organic fraction of municipal solid waste: Influence of co-digestion with manure. Water Research **39**(8), 1543-1552 (2005). doi:http://dx.doi.org/10.1016/j.watres.2005.02.001

25. Zhou, Y., Zhang, Z., Nakamoto, T., Li, Y., Yang, Y., Utsumi, M., Sugiura, N.: Influence of substrate-to-inoculum ratio on the batch anaerobic digestion of bean curd refuse-okara under mesophilic conditions. Biomass and Bioenergy **35**(7), 3251-3256 (2011). doi:http://dx.doi.org/10.1016/j.biombioe.2011.04.002

26. Jensen, M.B., Møller, J., Scheutz, C.: Comparison of the organic waste management systems in the Danish–German border region using life cycle assessment (LCA). Waste Management **49**, 491-504 (2016). doi:http://dx.doi.org/10.1016/j.wasman.2016.01.035

27. Fruergaard, T., Astrup, T.: Optimal utilization of waste-to-energy in an LCA perspective. Waste Management **31**(3), 572-582 (2011). doi:http://dx.doi.org/10.1016/j.wasman.2010.09.009

28. Güereca, L.P., Gassó, S., Baldasano, J.M., Jiménez-Guerrero, P.: Life cycle assessment of two biowaste management systems for Barcelona, Spain. Resources, Conservation and Recycling **49**(1), 32-48 (2006). doi:http://dx.doi.org/10.1016/j.resconrec.2006.03.009

29. Franchetti, M.: Economic and environmental analysis of four different configurations of anaerobic digestion for food waste to energy conversion using LCA for: A food service provider case study. Journal of environmental management **123**, 42-48 (2013). doi:http://dx.doi.org/10.1016/j.jenvman.2013.03.003

30. Siegert, I., Banks, C.: The effect of volatile fatty acid additions on the anaerobic digestion of cellulose and glucose in batch reactors. Process Biochemistry **40**(11), 3412-3418 (2005). doi:http://dx.doi.org/10.1016/j.procbio.2005.01.025