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Results on the implementation of an innovative dehydrated biological waste to ethanol management scheme

A. Sotiropoulos, ¹✉

Phone 0030 6971899507

Email angeluoi81@gmail.com

G. Xydis, ²

N. Kontogianni, ¹

S. Vakalis, ¹

¹ Unit of Environmental Science and Technology, School of Chemical Engineering, National Technical University of Athens, 9, Heroon Polytechniou Str., Zographou Campus, 15773 Athens, Greece

² Department of Business Development and Technology, Aarhus University, Birk Centerpark 15, 7400 Herning, Denmark

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Abstract

The results of the 2 years of operation of a dehydrated biological waste to ethanol management and treatment scheme are presented within the context of this work. This state-of-the-art and innovative biological waste management scheme was implemented in two major Greek Municipalities. The purity level of the incoming material was almost 100% w/w (99.99% w/w), while a significant variation in the biological waste material properties has also been recorded not only between seasons but also on a yearly basis. The results also revealed that the average energy consumption of the waste dryer was found to be 0.9 kW h/kg, while it ranged between 0.89 and 0.91 kW h/kg. The mass reduction achieved was 82% w/w, while the maximum ethanol production without the use of further additives was 11.5% w/w which is considered to be a worth to further optimize performance. The use of commercialized enzyme products under specific conditions has revealed that almost 90% w/w of the

starch, 50% and 40% w/w of the cellulose and hemicellulose, respectively, have the potential to be converted into sugars in order to be further treated for ethanol production.

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Keywords

Waste management

Drying

Biofuels

Bioeconomy

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Introduction

The future depletion of fossil fuels constitutes a significant challenge to human societies since fossil fuels play an important role not only for the energy sector but also for the existing fossil fuel-dependent markets, since their existence is related to the production of numerous chemical blocks, secondary materials and tertiary materials such as paints, textiles, cement (Werpy and Petersen 2004) which are important for the human civilization, as it is today. The fact that there is still a high dependence on fossil fuels worldwide which was still almost 81% in 2014 according to IEA (2017), while there is still an ongoing economic crisis (IMF 2016) with incalculable consequences, adding the fact that the technology readiness level (TRL) (Sadin et al. 1988) of already existing technologies in the biotechnological sector is still rather low, constitutes a significant challenge and future problem to a future state's bioeconomy growth as part of a state's circular economy strategy (EC 2015).

Municipal solid waste (MSW) constitutes a significant problem in all continents since concrete and sustainable treatment has not been provided up until today. Based on (World Bank 2012) data, almost 1.3 billion tons of food waste are produced per year, out of which, according to IPCC (1997), more than 2/3 of the total amount of MSW is comprised of food waste and paper/cardboard waste. Both of these waste fractions are degradable; thus, they are estimated to contribute to the production of GHGs of about 3.3 billion metric tons per year. The fact that this waste fraction is degraded due to the microbial activity, its water content and the elevated temperatures (Sotiropoulos et al. 2015) and produces GHGs not only during their initial disposal but also during their transport, treatment and final disposal constitutes a significant challenge which has not been tackled up until now.

There is a significant legislative framework at EU level such as the waste framework directive (2008/98/EC) which sets target to the maximum amount of biodegradable waste which should be sent to landfills up until 2020. This framework though sets targets regarding the reduction in this fraction without setting any sustainability targets for it. As part of a circular economy and bioeconomy strategy, this waste fraction should first be prevented and afterward it should be prepared for recycling based on EC legislative framework.

Many researchers have discussed and made significant research on the use of the biodegradable fraction of MSW: biological waste (bio-waste) and paper waste (Gwak et al. 2017; Rättö et al. 2009; Van Wyk 2001). All of them have stressed the potentials of this waste fraction.

Bio-waste drying for the production of ethanol is a concept which was first introduced by Sotiropoulos et al. (2015), as an alternative method of not only reducing the mass and volume of the target material drastically, but also as a method of preserving the material's carbohydrate content which is really important for a series of biotechnological processes. Bio-waste drying has been proven to produce a pre-treated material which could be safer transported and become a commercial biomass material which could solve the problem of already existing facilities that treat raw bio-waste having significant problems during handling, storage and treatment (low efficiency).

Almost 90% w/w of MSW produced in Greece (Eurostat 2017) are still sent to landfills, while there is an urgent need to prevent the bio-waste fraction from going to landfills, which played an important role to the development of this waste management scheme.

The main aim of this work is to present the results of the 2 years of efforts to reduce the mass of bio-waste and stabilize it, thus achieving the targets set in the landfill directive, having it simultaneously pre-treated, in order to become a new resource with a high chance to achieve economic sustainability in the near future. This research also presents the numerical results of the bio-waste drying process used in addition to the results of the ethanol produced through the use of the SSF process without the use of additives.

The research was conducted in Athens (Greece) at the premises of the National Technical University of Athens, for a period of 2 years [end of 2015 (start)–beginning of 2017 (end)].

Materials and methods

Methodology applied

The research was implemented in two major Greek Municipalities (Aspropyrgos and Papagos-Cholargos) of the Attica region. Both regions municipal solid waste (MSW) data have been described by Sotiropoulos et al. (2016). In total, 200 households participated in the implementation of the waste management scheme by providing raw household lignocellulosic biomass to the research team in order to be further treated for its bioconversion to biobased ethanol. The selection procedure and the methodology of the waste management scheme in both Municipalities have also been described by Sotiropoulos et al. (2016).

In brief, the bio-waste management scheme was operated by the Municipalities waste collection authorities. More specifically, kitchen waste bins (23 L) were provided to the participating households for the collection of the raw material. The material was placed in commercialized waste collection bags (not biodegradable since it was not required by the general operation of the scheme) available by all householders. The material inside the sealed, by the civilians', waste bags was then placed in brown waste bins (120 L) that were also provided by the Municipalities to the civilians.

The waste material that was placed in the waste bins by the civilians was comprised of all types of food waste (cooked and uncooked) including garden waste and kitchen paper waste, thus achieving the collection of the total amount of household bio-waste including a small, but important proportion of household biodegradable waste that cannot be usually recycled, such as kitchen paper waste.

The incoming substrate was manually sorted by the NTUA research staff based on Malamis et al. (2016) methodologies regarding the determination of the material purity level, while the pure separated lignocellulosic biomass was further pre-treated in order to reduce its mass and volume and preserve its lignocellulosic characteristics using the drum drying method (commercialized biomass dryer) as this has been described by Sotiropoulos et al. (2016), before it could be further utilized for the production of biobased ethanol.

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The material was further treated using commercially available enzymes and yeast in a 200-L bioreactor which design has been presented by Loizidou et al. (2017). The trials used to obtain the best of the results obtained while operating the bioconversion facility under the conditions described in Fig. 1 are recorded in Figs. 3 and 4.

Fig. 1

Bioconversion process schematic diagram

Methods of analysis

A large number of analyses were performed in order to assess important for the evaluation of the waste management scheme parameters. The following parameters were taken into account:

1. The purity level of the incoming household bio-waste was determined through optical sorting of the incoming bio-waste. The sorting took place each time the waste arrived at the NTUA facilities (Malamis et al. 2016).
2. The total mass of the incoming raw and the dehydrated material was measured using a digital scale before and after the dehydration process.
3. The energy consumption of the feedstock was measured directly with the use of an energy meter.
4. The determination of structural carbohydrates was performed based on Sluiter et al. (2004).
5. The determination of total reduced sugars, glucose content and ethanol was performed using the method described by Dogaris et al. (2009).
6. Crude protein in the substrate and the fermentation residue was estimated using Kjeldahl's method as described in AOAC methods (1995).
7. The bioconversion of the dehydrated material was implemented with the use of the 200-L bioreactor (Loizidou et al. 2017), while the operating

conditions involved two solids concentrations 35% w/v and 60% w/v, respectively, using the batch process. The enzymes products used were commercially available from Novozymes Corporation and were Spirizyme Fuel and Cellic CTec2 at a 15% w/w and 10% w/w with respect to the initial material's starch and cellulose content. The material was treated under the conditions that are recorded in Fig. 1. The process involved the sterilization of the target material for 30 min approximately at 120 °C and immediately afterward the enzymatic hydrolysis of the material using enzymatic products for the hydrolysis of cellulose, hemicellulose and starch. The Spirizyme Fuel HS was added for 1 h at ≈ 67.5 °C in order to break down the starch, while immediately afterward, Cellic CTec2 was added at ≈ 43.5 °C and for ≈ 4 h in order to break down the cellulose and hemicellulose. Finally, the Ethanol Red yeast mixture was added in order to convert the produced sugars into ethanol inside the original mixture. The parameters considered were the TRS, glucose, cellulose, starch and ethanol at different periods of the process in order to map the most efficient operation periods for the conditions that were used and provide an optimum operational map.

8. The ethanol produced was distilled using a laboratory distillation apparatus, and the purity of the distilled ethanol was measured using HPLC.

Results and discussion

Waste drying management scheme results

The material sorting process revealed the efficiency of this bio-waste to biobased ethanol waste management scheme regarding the purity level of the incoming material which was almost 100% w/w (99.99% w/w). This is a significant characteristic of the proposed waste collection process, since based on Sotiropoulos et al. (2016) most of the bio-waste collection schemes in most of the cases have shown not only lower purity levels but also significant variation which ~~varies between~~ ~~starts from~~ 95% w/w ~~and to~~ 99% w/w (Favoino 2003; Gibbs and Hogg 2007).

The quantity of household bio-waste including part of ~~the~~ household biodegradable kitchen paper waste that was provided to the project team was 25.770 kg for the whole period. The dehydrated material collected was 4600 kg which means that there was an 82% w/w mass reduction in the initial raw material mass. This means that ~~just~~ by dehydrating the raw incoming household material, the landfill directive targets may be achieved just by removing the bio-waste water content. This is an important parameter, ~~in addition to the fact that~~

there are ~~and that is the~~ concrete results regarding the mass and volume reduction, of this bio-waste to biobased ethanol management scheme.

The average energy consumption of the decentralized waste dryer was recorded equal to 0.9 kW h/kg, while it ranged between 0.89 and 0.91 kW h/kg. This is an amount of energy which should be taken into consideration when designing a waste management scheme, but the fact that the prices of solar and wind electricity production are dropping and the capacity increases (28.9% in 2016) based on REN21 (2016) report constitutes a significant parameter for the enhancement of the future environmental and socioeconomic efficiency of this scheme. A comparative study between decentralized waste drying method and household waste drying method has also been elaborated by Sotiropoulos et al. (2016), revealing the advantages in terms of energy consumption of the decentralized waste drying method.

A significant variation in the bio-waste material properties has also been recorded not only between seasons (Sotiropoulos et al. 2016) but also on a yearly basis. It should be stressed that there is a significant variation in these parameters from city to city, country to country and between different parts of the world depending on each region's bio-waste synthesis. In Table 1, the mean value of the material lignocellulosic characteristics after a 2-year period time is recorded.

Table 1

Household bio-waste chemical characterization/parameters related to lignocellulosic ethanol production

Parameter	Unit	Bio-waste
Water soluble	% d.m.	39 (varies between $\approx$ 35.7 and 43)
Total reduced sugars (TRS)	% d.m.	10.2 (varies between $\approx$ 6 and 14.5)
Glucose	% d.m.	1.9 (varies between $\approx$ 0.55 and 3.2)
Starch	% d.m.	12.3 (varies between $\approx$ 6.8 and 18.1)
Cellulose	% d.m.	16.4 (varies between $\approx$ 7.8 and 25)
Hemicellulose	% d.m.	4.1 (varies between $\approx$ 1.9 and 6.5)
Lignin	% d.m.	2.12 (varies between $\approx$ 1.9 and 2.3)
Protein	% d.m.	6 (varies between $\approx$ 3 and 9)

It should be stressed that there are no concrete data regarding the carbohydrate content of bio-waste and kitchen paper waste in bibliography. Many authors

have recorded different substrate materials, while no author has recorded a mean value of carbohydrates in a territory up until now.

Bioconversion process results

The following diagrams illustrate the results of the measurements conducted throughout the operation of the bioconversion facility under the operational conditions described. The evolution of the basic parameters related to the bioconversion process ~~were~~^{was} studied in order to conclude the best operational parameters for the facility.

Figure 2 presents the total reduced sugars (TRS) evolution as this was recorded during the system operation under different conditions.

Fig. 2

TRS evolution during the operation of the system (left), glucose (right)

Finally, Table 2 presents the results of the ethanol produced throughout the processes tested.

Table 2

Ethanol production for different operating conditions

Trials	Ethanol production (g/L)	Ethanol (g/100 g dw)	Ethanol production (g/L h)
A'	36	10.29	2.25
B'	40	12.43	2.5
C'	42	10.02	2.53

D' Trials	50 Ethanol production (g/L)	8.33 Ethanol (g/100 g dw)	3.13 Ethanol production (g/L h)
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From Fig. 3, it is derived that the starch needs 2 h in order to be fully hydrolyzed using these conditions without the use of any chemical additives, while the best conditions for the highest hydrolysis rate have been achieved for trial B (90% w/w conversion rate). Trial A conversion rate was also significantly high, while it reached 89.9% w/w conversion rate.

Fig. 3
Cellulose content conversion rate during the operation of the system (left), starch content (right)

For the case of cellulose (Fig. 4), it takes 6 h to be hydrolyzed by 52% w/w which has been achieved in trial A. The bioconversion of the structural carbohydrates with the use of commercial cellulases and α -amylase for sugar production needs 6 h to be fully completed for all cases studied.

Fig. 4
Glucose kinetics during the fermentation process

The ethanol production reached its maximum values ($\approx 12.43\%$ w/w) in trial B which is considered to be significant. ~~Other authors such as~~ Matsakas et al. (2014) have reported almost 12.5% w/w of ethanol production by using chemical additives to their process and by implementing batch experiments at a laboratory scale, while Alamanou et al. (2015) have reported a maximum of 10.7% w/w ethanol production by also using chemical additives and by performing batch experiments.

Other authors have reported different ethanol yields by using different substrates. Such example studies are Man et al. (2010) which reported ethanol production of 24.17 g/L, while Moon et al. (2009) reported 29.1 g/L, both by performing batch experiments and food waste as a substrate.

A hypothetical process chart that could be used for the production of ethanol considering approximately 10% w/w of ethanol production (less than the results of this manuscript) and treatment of the final residue through anaerobic digestion is presented in Fig. 5.

Fig. 5

Process schematic diagram

Conclusion

The 82% w/w mean mass reduction is expected to provide a concrete solution to a waste management authority since no other waste management scheme provides significant bio-waste mass minimization.

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The 11.5% w/w ethanol productivity without the use of chemical additives to the process should be considered an advantage compared to other methodologies since at a larger scale (TRL) the use of chemicals is expected to contribute negatively to the sustainability of the process. Finally, the fact that the operating conditions have been precisely determined is considered to be promising for the upscale of the proposed waste scheme. Depending on each region's bio-waste reduction targets and development plan, the dehydrated household bio-waste to ethanol management and treatment scheme may be applied in a sustainable and viable way, but further research toward this direction needs to be implemented.

The future research involves the determination of the actual economic and environmental feasibility of the system through its establishment and operation at a larger scale (five Greek Municipalities) and the comparison of the results

achieved through this study, with the results that will be obtained. Through this research, the drying and SSF processes parameters will be further optimized in order to provide a viable for the Municipalities solution.

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AQ6