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Domestic biowaste drying as a pretreatment method to produce a stabilised biological resource

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Abstract: The results of the use of the domestic biowaste drying method for the effective dehydration of the OFHMSW and the production of lignocellulosic biomass from this waste fraction are presented within this article. It presents the methodology and results produced from the first laboratory operation of a prototype household waste dehydration unit for the drying of household biowaste at source through the effective removal of its water content by using the heated air-drying process. The use of domestic dehydration technique revealed the substantial mass reduction that reached a maximum of 78%w/w, while the final product's carbohydrate content and suggests its further use to produce biobased chemicals and bioenergy. 39.99%w/w of the target material, more than 40%w/w of the material may be converted into sugars through fermentation and from there to ethanol. Moreover, 36.11 of the already existing sugars have the potential to be directly fermented to ethanol. Finally, considering a cost of 0.071 euro/kWh which is the mean value cost per kWh for the Greek household and energy consumption of 1,001–1,200 kWh which is also the average consumption of the Greek household, the maximum monthly cost for a family and a 24h operation was calculated to be 7.2 euros.

Keywords: biowaste; biobased; drying; bioeconomy; lignocellulosic biomass; resource efficiency; biomass; waste treatment.

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George Xydis worked on various wind energy projects that range from a single 10-kW turbine to a 486 MW offshore wind farm. He had the opportunity to work in the wind sector together with developers, utilities, constructors, universities, and research institutes. He also worked as a waste management expert at the National Technical University of Athens. He holds a PhD in Engineering from National Technical University of Athens, and a degree in Mechanical Engineering from Aristotle University of Thessaloniki. George is now an Associate Professor at the Department of Business Development and Technology, Aarhus.

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Stergios Vakalis currently works at the Faculty of Science and Technology of the Free University of Bozen-Bolzano. He does research in biomass gasification/pyrolysis, thermodynamic modelling and waste-to-energy. His assigned position is related to the development of the new ‘bioenergy and biofuels lab’ at the NOI Techpark. He is an Environmental Engineer with specialisation in renewable energy technologies, waste-to-energy, solid waste management, gasification of biomass, thermodynamic modelling, energy efficiency, onsite monitoring of energy plants and materials characterisation.

1 Introduction

European policy focuses on actions taken towards resource efficiency, circular economy and climate change adaptation and mitigation. A concrete strategy on circular economy and resource efficiency has not been elaborated up until now, while targets set by the EC legislative framework regarding the drastic reduction of GHGs that play a key role regarding the negative impacts of climate change, have not been defined per sector. The EC has already adopted the strategy *Innovating for Sustainable Growth: A Bioeconomy for Europe* (European Commission, 2012) which amongst others, prompts member states to use alternative lignocellulosic biomass resources instead of fossil fuels, to produce

biobased chemical and bioenergy. The OFHMSW is rather high in terms of quantity in all continents while it varies significantly when it is considered as a proportion of the total amount of MSW. More specifically, the quantity of organics varies between 47%w/w in Europe and Central Asia and 62%w/w in East Asia and Pacific (Hoorweg and Bhada-Tata, 2012). Food waste comprises the largest fraction of the total amount of the OFMSW worldwide. The water content of food waste also varies significantly and according to Diaz et al. (2005) it varies between 70–80%w/w while based on Zhang and Matsuto (2010) it varies between 75–95%w/w. The point is that the water content is significantly high in most of the cases.

The OFHMSW, is biodegradable hence, it is required to prevent its uncontrolled decomposition, to handle and treat this fraction in a sustainable way. Authors that have been using controlled processes such as composting, have related compost stability to microbial activity (Hue and Liu, 1995; Bernal et al., 1998), but others have related the material's stability to the loss of its mass. As a rule, it could be stated that if the OFHMSW is not stabilised, its biodegradation will lead to the loss of its carbohydrate and water content due to the microbial activity which, due to the biochemical reactions that take place during the biodegradation process, decompose the target material by absorbing its carbohydrates. The time of its decomposition varies and depends on the material's properties, its water content, the microbiological content and the temperature. Since the removal of microbes, nutrients are difficult to take place, the removal of the materials water content could be considered as a possible approach. Based on Barlaz et al. (1990) and Rodriguez et al. (2001), the water content of food waste materials under which no biodegradation activity takes place varies between 15 and 50%w/w.

Alternative economically and environmentally safe ways of stabilising waste biomass should be developed and demonstrated to enhance the use of the OFHMSW in the BBI. The use of domestic dehydration method of the source separated OFHMSW, can assist towards this direction and minimise transport and energy costs while creating a stabilised and easy to store and handle additional resource, for it to be further utilised to produce biobased chemicals and bioenergy. The domestic waste drying method involves the dehydration of the wet substrate of the OFHMSW with the use of a domestic drying system for the effective removal of the material's water content and the production of a significantly reduced in terms of mass and volume, biomass. This method has firstly been developed and recorded by Sotiropoulos et al. (2015b). The final dry product is a pure, stabilised material which can be stored, handled and transferred easily, while it contains significant amounts of structural carbohydrates.

There is a substantial number of sugar-based chemical building blocks and chemicals that may be produced from lignocellulosic feedstocks such as the OFHMSW as have been recorded by Werpy and Petersen (2004). All the existing processes use different microbial cultures to ferment diverse types of sugars, producing a great variety of biobased building blocks, secondary chemicals and materials. These sugar derived products may be utilised as an economic driver for a sustainable biorefinery concept worldwide.

The aim of this work is to present the first results of the operation of an innovative domestic waste dryer, for household use. The novelty of this work lays on the fact that the use of the domestic waste drying method has never been tested in the past at a

laboratory scale, even though there are some existing commercial waste dryers. This method could be quite promising since biowaste at a stabilised form could provide an alternative biomass resource. Moreover, a certain methodology should be developed in order to obtain reliable results on domestic waste drying. This work presents not only the results on the operation of the prototype waste drying unit but also the methodology developed and used for the testing of the prototype unit.

2 Materials and methods

2.1 Description of the domestic waste drying prototype

The prototype domestic waste dryer that was tested in terms of its drying performance, has been developed by Sotiropoulos et al. (2015a) in the framework of the LIFE 08 ENV/GR/000566 project with the acronym ‘DRYWASTE’. The prototype system has been designed with the use of appropriate 3D CAD software.

The main parts of the prototype domestic waste dryer have been described by Sotiropoulos et al. (2015a). The system produces the dry material by using heated air coming from its base.

For the needs of the research, the prototype unit operated for a period of 6 months under different operating conditions.

Before the initiation of the experiments, different food waste samples were physicochemically analysed in terms of their moisture content before making the substrate material for the drying experiments. The material was comprised of uncooked fruits and vegetables coming from local grocery stores in order to have a stable mixture of food waste. The food waste samples were collected daily. The substrate material was cut into pieces with the use of a kitchen knife unevenly in a way that simulates real conditions inside households. The substrate’s qualitative-quantitative data and the drying temperatures considered are presented in Table 1.

Table 1 The substrates qualitative-quantitative data

<i>Specimen</i>	<i>Mass (= 500 g–750 g)</i>	<i>Temperature</i>
1	Orange-lemon-cucumber-onion-apple	60-70-80°C
2	Orange-lemon-tomato-apple	60-70-80°C
3	Potatoes-lemons-apple-pear	60-70-80°C
4	Tomato-orange-apple-beans	60-70-80°C
5	Tomato-orange-apple-pineapple	60-70-80°C
6	Beans-cucumber-tomato-onion	60-70-80°C
7	Pepper-tomato-cucumber-melon	60-70-80°C

The samples were placed inside the waste dryer for the drying process to take place while their mass was measured every 30 minutes for a period of 8 hours. The samples were not left in a desiccator to cool down before measurement because the scientific team did not want the drying process to be disturbed throughout the measurements. Thus, the mass measurement was conducted in a temperature close to the drying temperature for a

1 minute maximum. Finally, the dried product after the 8-hour period was dried completely in an oven at 105°C to measure the final dry product's carbohydrate content. The experiments for all cases were replicated at least 8 times in order to obtain concrete results.

During this period the scientific team considered among others the following parameters to evaluate the system's overall performance:

The substrates mass reduction through time at three (3) different temperatures and for two (2) different masses with the use of the Mettler Toledo MS-TS Series Precision Balance MS12002TS; The temperature and humidity variation inside the system throughout the drying process by using the EL-USB-2-LCD Lascar electronics temperature and humidity datalogger:

- the energy consumption of the device was measured using an commercialised energy meter (Votcraft Energy 3000)
- the water content of the collected biomass throughout the drying process, was determined after drying the collected samples at 105°C for approximately 24 h
- the structural carbohydrates that were determined based on Sluiter et al. (2004)
- the total reduced sugars and glucose content that was determined using the method described by Dogaris et al. (2009).

Some of the equipment used for the experiments conducted can be seen in Figure 1.

Figure 1 (a) IR meter (b) Energy meter (c) prototype waste dryer (see online version for colours)

3 Results and discussion

3.1 Food waste moisture content

The moisture content of several types of food waste material was measured before the initial operation of the prototype waste dryer to determine the water content of food waste existing in households. The results are recorded in Figure 2.

From Figure 2, it can be seen that the moisture content of most of the food waste that were studied was above 60%w/w and may reach up to 94%w/w.

Figure 2 Moisture content of several types of food waste (see online version for colours)

3.2 Food waste samples mass reduction during the waste drying process/internal monitor of the drying chamber

Figure 3 illustrates the water content loss of the waste samples studied every thirty minutes for both masses and all three temperatures considered. Figure 3 illustrates the moisture reduction for a temperature of 60°C and two different masses (500 and 750 g), the moisture reduction for a temperature of 70°C and for both masses studied (500 and 750 g) and the water content reduction for a temperature of 80°C and two different masses (500 and 750 g).

Figure 3 Water content reduction at a temperature of 60°C, 70°C, 80°C respectively (blue is for 500 g and red for 750 g)

From Figure 3, it is observed that they all follow the pattern described by Krokida et al. (2003) for various fruits and vegetables and by Sotiropoulos et al. (2015b) for several types of waste. Moreover, the water content reduction is higher for 500 g for all three temperatures (60, 70 and 80°C). At 80°C the water removal is more effective for both

masses considered. For temperatures 60 and 70°C for the first two hours of the drying process, the moisture removal is almost the same for both masses (500 and 750 g). Moreover, the final water content of the dehydrated material was above 20%w/w for both temperatures.

At 80°C the moisture removal is more effective in all masses and all the drying times considered and for all the substrates used. The maximum mass reduction of the dehydrated material was approximately 70%w/w. At 80°C, the water content falls below 15%w/w which is an indicator of almost complete lack of biodegradation (Sotiropoulos et al., 2015b).

At 80°C the moisture removal is more effective in all masses and all the drying times considered and for all the mixtures used. Therefore, this temperature was chosen by the scientific team for the operation of the waste dryer at 20 households at a second stage during the project's implementation.

Figure 4 (a) Temperature and humidity variation inside the system for 80°C temperature with no waste inside the system, temperature and humidity variation inside the waste dryer when it operated with 500 g of wet mass for a 6-hour period at 60, 70 and 80°C (b) temperature and humidity variation inside the system for different temperatures (see online version for colours)

(a)

Figure 4 (a) Temperature and humidity variation inside the system for 80°C temperature with no waste inside the system, temperature and humidity variation inside the waste dryer when it operated with 500 g of wet mass for a 6-hour period at 60, 70 and 80°C (b) temperature and humidity variation inside the system for different temperatures (continued) (see online version for colours)

Even though composting and AD are processes that are used for the treatment of food waste, they can also be considered as processes for this waste fraction mass reduction through the material's organic carbon content reduction (Zhang et al., 2007). Authors using household composting process for the treatment of food waste, have reported a maximum 56%w/w mass reduction (Vich et al., 2015) (due to water and nutrients loss) while data regarding AD mass reduction are scarce.

During the drying process a data logger monitored the temperature and air humidity inside the waste dryer every ten minutes. This was implemented to monitor these parameters in real time for all the experiments conducted for the further optimisation of the prototype system to take place.

From Figure 4, the air humidity and temperature inside the drying chamber have a close relation (directly proportional). The air moisture inside the chamber is high at the beginning of the drying process while it can be attributed mainly to the water content of the food waste inside the drying chamber. The moisture also comes from the air coming from the environment. During the drying process the moisture is reduced with time until it reaches its minimum values.

From Figure 4, the relative humidity is inversely related to the temperature inside the dryer (the higher the temperature the lower the humidity). This is a well-known phenomenon when it comes to meteorology but when considering food water and the production of a waste dryer, this data is important since the installation of an air moisture sensor may be considered at a second stage to provide an automated waste drying system which is now operating by using a timer.

3.3 Temperature at the outer part of the prototype system

During the testing period, the temperature of the external part of the waste dryer (drying chamber) was monitored with an IR thermometer in order to have a complete picture of what is happening outside the dryer during, the drying process since no insulation material for the waste dryer was used.

The scientific team wanted to make sure that the waste dryer would not be dangerous to civilians. The results of temperature measurement are recorded in Figure 5.

Figure 5 Temperature measurements at the external part of the drying chamber (see online version for colours)

Based on Figure 5, the temperature difference from the inside to the outside is 18°C at 60°C, 19°C at 70°C and 23°C at 80°C. The 57°C max temperature means that the device is safe for the civilians since this temperature does not cause burns. An insulation system should be added to the drying chamber at a second stage though to improve the energy sustainability of the prototype.

3.4 Energy consumption

During the preliminary experiments the energy consumption of the device was also measured in all temperatures considered. An energy meter was used for the purpose of this study.

The results for the energy consumption measurements are recorded in Table 2.

Table 2 Energy consumption for every temperature considered

Temperature (°C)	Energy consumption KWhs/24h	Energy consumption KWhs/8h	Energy consumption KWhs/month 8h	Monthly operational cost (euros/month)	Energy consumption KWhs/month 24h	Monthly operational cost (euros/month)
60	2.2	0.73	21.9	1.53	66	4.69
70	2.8	0.93	27.9	1.98	84	5.96
80	3.4	1.13	33.9	2.41	102	7.2

Considering the worst-case scenario that the device needs to operate for a period of 24 h constantly for thirty days per month, the device energy consumption is presented in Figure 6.

Figure 6 Device energy consumption for 24-hour operation and a 30 days continuous operation (see online version for colours) **Figure 7** Cost of the operation of the device for a 24h operation 30 days per month (see online version for colours)

Considering a cost of 0.071 euro/kWh which is the mean value cost per kWh for the Greek household and energy consumption of 1,001–1,200 kWh which is also the average consumption of the Greek household, the cost that comes from the operation of the device is presented in Figure 7.

3.5 Structural carbohydrates of the dehydrated food waste

The structural carbohydrates of the final dry material are recorded in Table 3.

Table 3 Food waste lignocellulosic properties

<i>Food waste properties</i>	<i>Unit (%w/w)</i>
Cellulose	16.3
Hemi-cellulose	17.12
Starch	5.45
Total sugars	36.11
TRS	7.22
Glucose	1.12

From what it can be seen from Table 3, 39.99%w/w (cellulose, hemi-cellulose, starch, glucose) of the target material, may be converted into sugars and through fermentation to ethanol. Moreover, 36.11 of the already existing sugars have the potential to be directly fermented to ethanol. Ethanol is a bio-based material that may also produce ethylene, PVC, etc. if treated properly. Thus, it is considered that the produced biomass may be used as an alternative source for biobased materials production.

3.6 Future work

This work presents the first laboratory scale experiments results on the domestic biowaste drying technique that has not been tested by many scientists in the past and has the potential of being an alternative biowaste management and treatment method for the sustainable management of biowaste. This method looks promising for achieving the targets set by the landfill directive 1999/31/EC which obliges member states to reduce the amount of biodegradable waste that they landfill to 35% of 1995 levels by 2020.

The next logical research steps should be:

- a the optimisation of the prototype waste dryer regarding the time taken for the drying process to be completed
- b the system should be tested in terms of its economic feasibility and environmental viability, while an LCA analysis on the whole biowaste drying cycle should be conducted
- c its pilot scale testing in real household to obtain justification results regarding the system's mass and volume reduction and its energy consumption
- d The further research on the bioconversion of the final dehydrated product into biobased products and materials.

4 Conclusions

Concluding, it is stressed that the main characteristics of this process are the concrete results it produces since a substantial mass reduction takes place at source (78%w/w at 80°C and 8 hours operation for 500 g) while the material's biodegradation is inhibited and can be stored for an extended period before it is collected and transferred for further treatment.

At a first glance, the system may operate without being dangerous to the public since the temperatures that were noticed at the outer part of the dryer are not considered to be harmful to users. Finally, the energy consumption of the device is not considered to be high in comparison to the benefits for the environment though further research need to be done to that direction and regarding different waste management schemes in order to obtain a wider picture of this technology viability. Finally, the carbohydrate content of the dried food waste is considered to have the potentials to produce ethanol and other biobased materials since the absence of microbial content, the fact that it has already been pre-treated and pulverised, makes it an easy target lignocellulosic material for a saccharification process.

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Abbreviations

<i>a/a</i>	<i>Abbreviations</i>	<i>Meaning</i>
1	AD	Anaerobic digestion
2	BBI	Biobased industry
3	CAD	Computer-aided design
4	EC	European Commission
5	GHGs	Greenhouse gases
6	MSW	Municipal solid waste
7	OFHMSW	Organic fraction of household municipal solid waste
8	PVC	Polyvinyl chloride
9	TRL	Technology and research level