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Quantitative characterization of carbonaceous and lignocellulosic biomass for anaerobic digestion

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ABSTRACT

Biochemical quantitative characterization of biomass is becoming of key importance with the awareness and implementation of the fourth industrial revolution *(FIR)* and specifically in waste to energy recovery technologies. In this study, we investigated the quantification, characterization and anaerobic digestion of organic fraction of municipal solid waste *(OFMSW),* sewage sludge, animal manure and agricultural waste as a substrate for potential alternative clean fuel production to meet the ever-rising energy demand. The basis of comparison included ultimate analysis and proximate analysis for better understanding of the characteristic of biomass for waste to energy application. Existing quantitative and characterization methods for physical and chemical properties were analyzed and reviewed using collected samples. The substrates analysis showed physio-chemical properties of significant energy value, like that of natural gas. Biochemical methane potential test *(BMP)* showed high feasibility for methane production with mono and co-digestion of animal waste, sewage sludge, *OFMSW* and agriculture waste. The results of the quantitative characterization and *BMP* test would contribute to affordable, sustainable, reliable, carbon-neutral form of modern energy and development of adequate waste to energy recovery management strategies.

1. Introduction

The fourth industrial revolution, population growth, economic development, urbanization and improvement in living-standards has increased waste generation and introduced emerging contaminants into waste streams that may pose sanitary and environmental risks [1–3]. The emerging contaminants of concern include pesticides, flame retardants, pharmaceutical, various fluorinated compounds, plasticizers and nanomaterial [4]. These contaminants end up in landfills and water bodies, leading to pollution of the environment thus putting a strain on economic, social and health sectors [4,5]. The rapid increase in the quantities of waste generated demand a wider coverage of existing waste management system that provides sustainable standards for innovative treatment alternatives and technologies. Achieving these standards requires the quantitative characterization of given waste streams and implementation of integrated waste management systems [6]. Reliable waste management data provides an all-inclusive resource for a comprehensive, critical and informative evaluation of waste management options in all waste management programs [7,8].

Carbonaceous materials, such as animal waste, sewage sludge, *OFMSW,* and agriculture waste can be used as a substitute for fossil fuel [5]. The carbonaceous substrates can be converted into energy by biological conversion [9,10] or by thermochemical processes, such as pyrolysis [5,11], gasification [1,5,12], combustion [13], incineration [14,15] and liquefaction [5]. Full-scale mechanical pre-treatment *(MPT)* could be used to remove inhibitive conditions for successive biomethane/biogas production in landfill thus reducing total waste impact [16,17].

In the past, biomass characterization and quantification through identification of biochemical families have become crucial in several topics of environmental treatment processes. Later, with a growing necessity to optimize and model treatment process performance, a more accurate and detailed quantification and characterization of biomass was required [18–20]. Knowledge of biomass composition is necessary for adequate urban life cycle assessment of integrated solid waste management [21,22]. Integrated municipal solid waste management

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systems *(IMSW-MS)* provide an adequate guide to the treatment of collected waste with minimal environmental impact, reduction of wastes before they enter the waste streams, recovery of generated waste for recycling and sound disposal at an affordable cost. It compasses of the generation, handling, temporary storage, collection, transfer to final disposal and utilization of waste, waste treatment and energy recovery [23]. Management of waste continues to be a high priority in the 21st century. This is a requirement for future planning. There are several obstacles confronting municipal solid waste (*MSW*) management within the major cities. Some of such obstacles are: complexity of the waste stream due to the different living standards within the city; interrelation of urbanization and economic growth; lack of adequate facilities that will expedite waste separation at source; overstretching of the superannuated infrastructure; and also the waste management technologies that are costly compared to the cost of landfilling [21,24]. Separation of waste at the source (use of waste transfer stations) has achieved some degree of success. The option of energy recovery is highlighted in the waste management hierarchy from most favoured option to least favoured option as reduce, reuse, recycling, energy recovery and disposal respectively [21,24,25].

Environmental management has three concepts of *R's i.e.* reduce, reuse and recycle which are part of a cleaner production that concentrate on pollution prevention at source rather than the endpoint. This is vitally important in the protection of the environment from pollution and better utilization of resources [26]. According to Finnveden et al, (2005) [25], the waste hierarchy is often suggested and used in waste policy-making. Hierarchy of *MSW* follows the following models: reduce the amount of waste, reuse, recycle material, incinerate with heat recovery and landfill. The first priority, reduction of the amount of waste is generally accepted. However, the remaining waste needs to be utilized efficiently where different options for waste utilization need to be studied. The hierarchy after the top priority is often contested and discussions on waste policy are in many countries intense and as well as the order regarding recycling and incineration. Another big question is where to place biological treatments such as anaerobic digestion and composting in the hierarchy [25].

Adoption of *WtE* technologies pathway is an effective way to harness energy from biomass and to reduce greenhouse gases *(GHG)* emission from biomass. Various *WtE* technologies include; thermochemical (pyrolysis, incineration, gasification, liquefaction, combustion *etc.*) and biochemical (anaerobic digestion (*AD*) or biogas production, composting *etc.*) [27].

Biogas is a mixture of gases such as methane (CH_4), carbon dioxide (CO_2), ammonia (NH_3), hydrogen sulphide (H_2S) and the trace amounts of hydrogen (H_2), oxygen (O_2) and carbon monoxide *(CO)*. Biogas is produced by the breakdown of carbonaceous and lignocellulosic biomass using bacteria under controlled variables [28,29]. The organic matter is composed of biodegradables such as the *OFMSW,* animal waste, agricultural waste and industrial waste [30,31]. Bioenergy derived from biogas is used in the form of electricity, heat, and fuel. It is desirable to create an affordable, sustainable worldwide energy system with zero carbon emissions.

The production of biogas takes place in series of four fundamental steps namely: hydrolysis, acidogenesis, acetogenesis and methanogenesis [32–34]. Pretreatment of biomass is added as a preliminary step and includes mechanical, chemical and biological pretreatment [35]. Various parameters control the efficiency of the *AD* process. When these parameters are optimised, they provide an appropriate environment for the growth of anaerobic micro-organisms that yield the biomethane. These parameters include: nutrient supply (carbon-nitrogen ratio) [36,37], constant temperature [38–40], pH [38,41,42], stirring intensity/agitation [38], retention time [38,43], digestion chamber loading [44,45], particle size [38] nature of substrate [46], long chain fatty acids [47–49], optimum trace element concentration [50], grinding [51], co-digestion [9,50], presence and amount of inhibitors (*e.g.* volatile fatty acids *(VFA)*, ammonia, and trace metals in high concentration beyond threshold) [9]. Anaerobic digestion should take place in the absence of oxygen to support the survival of methane-forming bacteria [40,52].

1.1. *Types of biomass and characteristics related to anaerobic digestion*

Biomass originates from organic matter. Biomass is not of fossil origin; however, it can be used for energy recovery. When produced from living biological organisms, it is considered as renewable (green) energy [12]. Biogas is produced from biodegradable organic matter such as sewage sludge, animal waste, *OFMSW,* and energy crops and septic tanks. The most common biomass types used in European biogas production are listed below as [53].

- ➢ Sewage sludge from the wastewater treatment plant.
- ➢ Animal waste and by-products.
- ➢ Energy crops (maize, clover, sorghum, miscanthus *etc.*).
- ➢ Organic fraction from catering and municipal waste.
- ➢ Digestible organic wastes from agro-industries and food.

The waste can be used raw (as discarded) or pre-treated before *AD* process. Substrates could be classified according to various criteria due to the diversity of substrates' characteristic such as: carbon to nitrogen *(C/N)* ratio, dry matter content *(DM) or* total solids *(TS),* volatile solids *(VS),* moisture content *(MC),* calorific value *(CV)* and methane yield. A general overview of the characteristics of some biodegradable substrate types is presented by Noshy et al, (2013) [53]. Substrates that contain dry matter content lower than 20% are used for wet digestion. The wet digestion substrates are represented by animal waste (manure and slurries) and organic wastes from food industries. Dry matter content of up to 35% is considered to be dry digestion, and it is mainly used for energy crops [3,53]. Substrates that contain high amounts of cellulose, hemicelluloses and lignin need pre-treatment to enhance the digestibility and reduce these contents in the substrates [53]. The methane yield is considered one of the most important criteria in the *AD* process. It is used to evaluate for different types of *AD* substrates [53].

1.2. *Sustainability of the biomass for the anaerobic digestion*

The determination of the sustainability/availability of biomass (biodigester substrates) takes place in different approaches. All these independent channels yield varying results. The techniques used include feasibility studies that require direct measurements of the feedstock from source, use of existing data from the respective government, non-government and private institution on the previous studies and lastly on the peer-reviewed publications. However, physical measurement gives the most accurate results since data are not estimated against the source of waste generation [54]. The option for the determination of the sustainability of the biomass for the *AD* is outlined in a report by the United Nation Environmental Programme *(UNEP) as* [55,56]:

- ➢ Measurement of waste at the source of generation.
- ➢ Examination of records at the disposal facility.
- ➢ Through the use of integrated waste management *(IWM)* vehicle survey.
- ➢ Examination of records at the source of generation.

Measurement of the waste at the point of generation has been described as the most accurate and reliable means for determining the sustainability and the availability of the waste to energy technologies. However, it has been determined as the most expensive and time-consuming approach. This method involves carrying out sampling and analysis from the source of waste generation using appropriate procedures [55]. The accuracy of the method depends on the nature of the substrates. For this reason, specificity, interference and reliability test have to be carried out to validate the analysis [57].