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Pilot-scale anaerobic co-digestion of sewage sludge with agro-industrial by-products for increased biogas production of existing digesters at wastewater treatment plants

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ABSTRACT

Due to low degradability of dry solids, most of the digesters at wastewater treatment plants (WWTP) operate at low loading rates resulting in poor biogas yields. In this study, co-digestion of sewage sludge (SS) with olive mill wastewater (OMW), cheese whey (CW) and crude glycerol (CG) was studied in an attempt to improve biogas production of existing digesters at WWTPs. The effect of agro-industrial by-products in biogas production was investigated using a 220 L pilot-scale (180 L working volume) digester under mesophilic conditions (35 °C) with a total feeding volume of 7.5 L daily and a 24-day hydraulic retention time. The initial feed was sewage sludge and the bioreactor was operated using this feed for 40 days. Each agro-industrial by-product was then added to the feed so that the reactor was fed continuously with 95% sewage sludge and 5% (v/v) of each examined agro-industrial by-product. The experiments showed that a 5% (v/v) addition of OMW, CG or CW to sewage sludge significantly increased biogas production by nearly 220%, 350% and 86% as values of 34.8 ± 3.2 L/d, 185.7 ± 15.3 L/d and 45.9 ± 3.6 L/d respectively, compared to that with sewage sludge alone (375 ml daily, 5% v/v in the feed). The average removal of dissolved chemical oxygen demand (d-COD) ranged between 72 and 99% for organic loading rates between 0.9 and 1.5 kg VS m^{-3} d^{-1}. Reduction in the volatile solids ranged between 25 and 40%. This work suggests that methane can be produced very efficiently by adding a small concentration (5%) of agro-industrial by-products and especially CG in the inlet of digesters treating sewage sludge.

1. Introduction

Biogas is one of the most widely used types of renewable energy in European Union countries. In Greece, however, its use has not progressed correspondingly to date. Wastewater treatment plants (WWTPs) in all major Greek cities operate their own anaerobic digestion (AD) facilities in order to treat sewage sludge rather than achieve optimum biogas production.

The plants already installed and in operation could, with the addition of other types of waste, dramatically increase biogas production, yielding significant amounts of electricity and heat. This would simultaneously achieve the production of renewable energy and waste processing, without requiring additional facilities. Most urban and suburban areas of Greece produce the same products and therefore have to deal with the same waste. Particular mention should be made of the major agro-industrial units in Greece, such as wineries, cheese factories and livestock units. These wastes, which have very high organic load, could be used for anaerobic reactors already established and functioning in WWTPs which produce significant quantities of biogas.

Some agro-industries such as olive oil mills and cheese factories represent a considerable share of the Greek economy. The by-products of three-phase olive oil production such as olive mill wastewater (OMW) and olive cake pose a serious environmental risk. OMW is dark colored, with acidic pH and characteristic smell,

Abbreviations: AD, anaerobic digestion; WWTP, wastewater treatment plants; SS, sewage sludge; OMW, olive mill wastewater; CW, cheese whey; CG, crude glycerol; TS, total solids; VS, volatile solids; T-COD, total chemical oxygen demand; d-COD, dissolved chemical oxygen demand; N, nitrogen; P, phosphorus; OLR, organic loading rate.

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and though having a large organic load it presents low biodegradability (Azbar et al., 2004; Borja et al., 2006), due to the presence of inhibitory compounds such as phenols. The exact chemical characteristics of OMW can differ according to the olive variety and tree cultivation conditions, the extraction method used, etc. The organic load measured as COD is 40–220 g/L and includes organic compounds such as sugars, tannins, polyphenols, polyalcohols, pectins and lipids (Aktas et al., 2001; Azbar et al., 2004; Hamdi, 1993; Vlyssides et al., 2004). The total concentration of phenols which contribute to a high toxicity and antibacterial activity (Capasso et al., 1995) can reach 10 g/L (Borja et al., 1992). The solution adopted in many countries is evaporation in open ponds, which requires large areas and generates several problems such as bad odour, methane emissions, infiltration into the soil and insect proliferation (Roig et al., 2006; Jarboui et al., 2010). This means that common cost-effective practices applied to OMW management are not a suitable solution to this problem. As a result, significant OMW volumes in the Mediterranean area are discharged directly into watercourses (Azbar et al., 2009; El-Gohary et al., 2009) and it is urgently necessary to adopt technologies that can maximize the benefit-cost ratio and overcome this situation. One of the more effective ways to dispose of these wastes is using the anaerobic digestion process (Boari et al., 1984; Borja et al., 1993).

Cheese whey (CW) is a by-product of cheese manufacturing (Ferchichi et al., 2005; Kisaalita et al., 1987). The cheese manufacturing industry generates large amounts of CW, which is a high strength wastewater, with associated high biological (BOD_5) and chemical oxygen demand (COD) and a BOD_5/COD ratio commonly higher than 0.5 (Prazeres et al., 2012). CW is the most important waste stream produced, with a high organic content (up to 70 g COD/L) which is highly biodegradable, and low alkalinity (50 meq/L) (Mawson, 1994). The main contributors to the organic load of these wastes are carbohydrates, proteins and fats. CW contains a significant amount of carbohydrates (4–5%), mainly lactose (45–50 g/L), proteins (6–8 g/L), lipids (4–5 g/L) and mineral salts (8–10% of dried extract); mineral salts include NaCl and KCl (>50%), calcium salts and others. CW also contains appreciable quantities of lactic (0.5 g/L) and citric acid, non-protein nitrogen compounds (urea and uric acid) and B-group vitamins (Venetsaneas et al., 2009). Hence, this substrate is suitable for treatment by biological processes (Prazeres et al., 2012). However, despite its high BOD_5 and carbohydrate content, anaerobic treatment of raw CW is quite problematic due to its low bicarbonate alkalinity (50 meq/L), high COD concentration (up to 70 g COD/L) and tendency to rapid acidification (Prazeres et al., 2012). Whey has a pH of 5.9–6.6, while the manufacture of mineral–acid precipitated casein yields acidic whey, with a pH of 4.3–4.6 (Bylund, 1995). Whey management has attracted more attention due to stricter legislation (Farizoglu et al., 2004) and for economic reasons (Yang et al., 2007). From a wastewater treatment point of view, anaerobic digestion of cheese whey offers an excellent approach.

On the other hand, glycerol is a major by-product of biodiesel production. In general, for every 100 kg of biodiesel produced, approximately 10 kg of glycerol by-product is generated (Hazimah et al., 2003; Kolesarova et al., 2011). The significant increase in biodiesel production has created a glycerol surplus that has resulted in a dramatic decrease in crude glycerol prices (Yazdani and Gonzalez, 2007). However, EU directives have determined that the use of biodiesel should reach 20% of fuels used in 2020. Moreover, glycerol is a readily digestible substance which can be easily stored over a long period. As a result, glycerol can be an ideal co-substrate for the anaerobic digestion process. Despite the widespread applications of pure glycerol in the pharmaceutical, food, and cosmetic industries, the refining of crude glycerol to a high purity is too expensive, especially for small and medium biodiesel producers (Pachauri and He, 2006).

Many researchers have studied the influence of glycerol as a co-substrate in anaerobic digestion. During experiments in an upflow anaerobic sludge blanket (UASB) reactor treating potato processing wastewater, Ma et al. (2008) found that the biogas production increased by 0.74 L biogas per mL glycerol added. This means that glycerol is an attractive alternative for use and recovery through its co-digestion with other waste, as it is readily biodegradable and has a pH suitable for anaerobic processes, and there are a variety of microorganisms that use glycerin anaerobically as a carbon source (Da Silva et al., 2009). Anaerobic co-digestion of glycerol and a variety of residual biomasses may be a good integrated solution for managing these wastes and simultaneously producing a source of bioenergy in an environmentally friendly way.

Anaerobic digestion has many environmental benefits including the production of a renewable energy carrier, the possibility of nutrient recycling and reduction of waste volumes (Ghosh et al., 1975; Hawkes and Hawkes, 1987; van Lier et al., 2001).

The productivity of anaerobic digesters can be improved by supplementing with readily digestible co-substrates (Angelidaki and Ahring, 1997; Fountoulakis et al., 2008). The anaerobic co-treatment of organic wastes, known as co-digestion, is not often found in SS treatment facilities even though it is a common practice with agro-industrial wastes (Long et al., 2012; Mata-Alvarez et al., 2014). The objective of improved gas yield is based on an improved composition of the influent, since the co-substrates are usually complementary to the major waste in most cases, or due to an increased organic loading rate without changing the retention time.

Co-digestion is the simultaneous digestion of a homogenous mixture of two or more substrates. Traditionally, anaerobic digestion was a single substrate, single purpose treatment. Recently, it has been realized that anaerobic digestion as such becomes more stable when the variety of substrates applied at the same time is increased. The most common situation is when a large amount of a main basic substrate (e.g. manure or sewage sludge) is mixed and digested together with minor amounts of a single, or a variety of additional substrates (Braun, 2002). The use of co-substrates usually improves the biogas yields from anaerobic digesters due to positive synergisms established in the digestion medium and the supply of missing nutrients by the co-substrates (Mata-Alvarez et al., 2014). Braun (2002) presents several possible ecological, technological and economic advantages of co-digestion, such as improved nutrient balance for optimal digestion and good fertilizer quality, and increased, steady biogas production throughout the seasons.

Furthermore, co-digestion of organic wastes with municipal wastewater sludge can increase digester gas production and provide savings in the overall energy costs of plant operations. Methane recovery also helps to reduce the emission of greenhouse gases to the atmosphere. Thus renewable energy production and waste processing are achieved simultaneously, without requiring additional facilities.

Several studies have shown that, generally, the sensitivity and performance of the anaerobic digestion (AD) process may be improved by combining several waste streams. Co-digestion of different types of organic by-products has been increasingly applied in order to improve plant profitability and overcome a number of problems such as nutrient imbalance, rapid acidification and the presence of inhibiting compounds, among other factors (Cuetos et al., 2008; Fountoulakis et al., 2008; Macias-Corral et al., 2008; Martinez-Garcia et al., 2007; Monou et al., 2008a,b). Other advantages of this technology are potential improvement of methane yield (Macias-Corral et al., 2008) due to the supply of additional nutrients from the co-digestates and more efficient use of equipment and cost-sharing by processing multiple waste streams in a