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Review

Enhancing anaerobic treatment of domestic wastewater: State of the art, innovative technologies and future perspectives

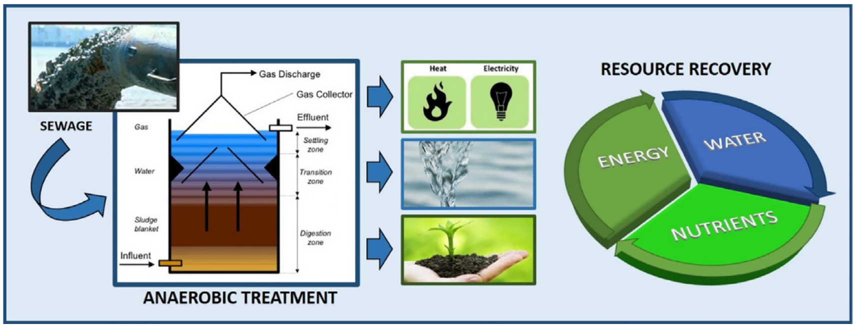
Valentina Stazi, Maria Concetta Tomei *

Water Research Institute, C.N.R., Via Salaria km 29.300, CP 10, Monterotondo Stazione, 00015 Rome, Italy

HIGHLIGHTS

- Anaerobic wastewater treatment allows energy production and resource recovery.
- Feasibility demonstration of effective anaerobic sewage treatment
- Performance analysis of high-rate anaerobic bioreactors
- Focus on promising innovative technologies and their potentialities
- Comparative analysis of high rate systems to define future research needs

GRAPHICAL ABSTRACT



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ABSTRACT

Recent concerns over public health, environmental protection, and resource recovery have induced to look at domestic wastewater more as a resource than as a waste. Anaerobic treatment, owing to attractive advantages of energy saving, biogas recovery and lower sludge production, has been suggested as an alternative technology to the traditional practice of aerobic wastewater treatment, which is energy intensive, produces high excess of sludge, and fails to recover the potential resources available in wastewater. Sewage treatment by high-rate anaerobic processes has been widely reported over the last decades as an attractive method for providing a good quality effluent. Among the available high-rate anaerobic technologies, membrane bioreactors feature many advantages over aerobic treatment and conventional anaerobic systems, since high treatment efficiency, high quality effluent, pathogens retention and recycling of nutrients, were generally achieved. The objective of this paper is to review the currently available knowledge on anaerobic domestic wastewater treatment for the mostly applied high-rate systems and membrane bioreactors, presenting benefits and drawbacks, and focusing on the most promising emerging technologies, which need more investigation for their scale-up.

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* Corresponding author.
E-mail address: tomei@irsa.cnr.it. (M.C. Tomei).

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1. Introduction

Recent concerns over public health and environmental protection, and the needs of resource recovery, imposed by the environmental sustainability, induced to look at domestic wastewater (DWW) not more as a waste to be treated or disposed of but as a source of valuable products. Potentially recoverable resources consist of water (produced from cleaner wastewater streams with advanced treatment technologies, or low tech and nature-based biological solutions if reused for agriculture purposes), fertilizing nutrients (nitrogen and phosphorus as main nutrients but also potassium and sulphur) and energy (Bae et al., 2014; El-Khateeb et al., 2009; Foresti et al., 2006; Kujawa-Roeleveld and Zeeman, 2006; McCarty et al., 2011).

Aerobic treatment is typically part of a multistage wastewater treatment process. Despite the very good effluents quality, this practice is energy intensive, produces high excess of sludge, which requires handling, treatment and disposal, and fails in recovering the potential resources available in wastewater (Leitão et al., 2006; Martinez-Sosa et al., 2011; Smith et al., 2012). Moreover, the traditional practice of aerobic treatment and anaerobic sludge digestion allows recovering only a small amount of the energy associated to the dissolved organic fraction, with the result that conventional approaches require more energy than producing through digestion (McCarty et al., 2011). To help solving such problems, anaerobic treatment, owing to attractive advantages of energy saving, biogas recovery and lower sludge production, has been suggested as an alternative technology (Bae et al., 2014; Chong et al., 2012; Wen et al., 1999) for DWW treatment.

McCarty et al. (2011) evaluated the potential benefits of anaerobic DWW treatment compared to a conventional activated sludge system coupled with anaerobic sludge digestion assuming a typical DWW whose Chemical Oxygen Demand (COD) concentration was 500 mg/L. They reported that with full anaerobic treatment, a doubling of CH_4 production, over conventional activated sludge system, is achieved, and energy production greatly exceeds the energy required for plant operation. This important result means that anaerobic DWW treatment can be a net energy producer.

Domestic wastewater is also an important carrier medium for nutrients in the nutrient cycle. Recycling nitrogen and phosphorus present in sewage rather than wasting them could allow minimizing the anthropogenic production of fertilizer. About resources harvesting, Verstraete et al. (2009) reported the potential product recovery from municipal "used water" summarized in Table 1.

Conversion processes in anaerobic digestion are catalysed by intra- or extracellular enzymes and both available soluble and particulate organic compounds can be biodegraded. Mostly complex polymeric substrates such as carbohydrates, proteins, and fats are hydrolysed to give simpler soluble products such as amino acids, sugars, fatty acids and glycerine, by the action of extracellular enzymes excreted by the fermentative bacteria. This hydrolytic step is the rate-limiting one in the overall anaerobic treatment for wastes containing fats and a significant amount of particulate matter (Khanal, 2008; Tomei et al., 2008). In the general model of the anaerobic process, it is assumed that fermentative bacteria initiate the catabolism producing acids and alcohols, which are then readily utilized as substrates by acetogenic bacteria to produce acetate. At the final stage, methanogens obtain energy from converting acetate, carbon dioxide, and hydrogen to methane (Schink, 1997; Tomei et al., 2009).

At first, anaerobic treatment was considered possible for high-strength wastewater and only for temperature conditions above 20–25 °C so that the first anaerobic reactor configurations were applied in tropical regions and designed for industrial wastewater (Foresti et al., 2006). However, more efficient technologies have been developed in the 1980s leading to suggest that the anaerobic digestion in the proper bioreactor configuration could be applied to treat even DWW at low temperature. Since then, there have been a number of applications of full-scale direct anaerobic treatment of DWW, particularly in developing countries such as Brazil, Colombia, Mexico, Egypt, and India, where this technology is considered to be a low-cost wastewater treatment alternative (Aiyuk et al., 2006; McCarty et al., 2011).

In general aerobic systems are suitable for the treatment of low-strength wastewaters (biodegradable COD concentrations < 1000 mg/L) while anaerobic systems are suitable for the treatment of high-strength wastewaters (biodegradable COD concentrations $>$ 4000 mg/L). Furthermore, aerobic systems, compared to anaerobic ones, achieve higher removal of soluble biodegradable organic material and the produced biomass is generally well flocculated, resulting in lower effluent Suspended Solids (SS) concentration. As a result, the effluent quality from an aerobic process is generally higher than in an anaerobic process. This latter, in fact, is not generally sufficient to meet stringent effluent requirements in terms of residual organic matter, SS, pathogenic microorganisms and possibly nutrients, thus often necessitating post-treatments. Aerobic reactors, physical-chemical processes or more "natural" alternatives like wetlands and oxidation ponds are employed as post-treatment units (Chan et al., 2009; Chernicharo et al., 2015; El-Khateeb et al., 2009; Kim et al., 2011; Van Haandel et al., 2006).

The lower efficiency of the anaerobic processes is due to a lower metabolic capacity of anaerobic bacteria resulting in longer retention times required in respect to the aerobic ones (Van Haandel et al., 2006). This critical aspect can be faced with the high-rate anaerobic systems, which have the ability to separate Hydraulic Retention Time (HRT) and Solid Retention Time (SRT) effectively, and quite low HRTs can be applied due to the accumulation of a high biomass concentration in the system (Daud et al., 2018; Gömec, 2010).

Table 1
Potential product recovery from municipal wastewaters (Verstraete et al., 2009).

Potential recovery	Per m^3 sewage
Water	1 m^3
Nitrogen	0.05 kg
Methane[a]	0.14 m^3
Organic fertilizer[b]	0.10 kg
Phosphorus	0.01 kg

[a] Methane produced per m^3 of sewage was calculated on the basis of 80% organic matter recovery as biogas with 0.35 m^3 CH_4/kg $COD_{removed}$.

[b] Organic fertilizer was calculated on the basis of 20% organic matter remaining after anaerobic digestion.