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Research review paper

Toxicants inhibiting anaerobic digestion: A review

Jian Lin Chen [a], Raphael Ortiz [b], Terry W.J. Steele [b,*], David C. Stuckey [a,c,**]

[a] Advanced Environmental Biotechnology Centre, Nanyang Environment & Water Research Institute, Nanyang Technological University, Singapore 637141
[b] School of Materials Science & Engineering, College of Engineering, Nanyang Technological University, Singapore 637141
[c] Department of Chemical Engineering, Imperial College London, London SW7 2AZ, UK

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ABSTRACT

Anaerobic digestion is increasingly being used to treat wastes from many sources because of its manifold advantages over aerobic treatment, e.g. low sludge production and low energy requirements. However, anaerobic digestion is sensitive to toxicants, and a wide range of compounds can inhibit the process and cause upset or failure. Substantial research has been carried out over the years to identify specific inhibitors/toxicants, and their mechanism of toxicity in anaerobic digestion. In this review we present a detailed and critical summary of research on the inhibition of anaerobic processes by specific organic toxicants (e.g., chlorophenols, halogenated aliphatics and long chain fatty acids), inorganic toxicants (e.g., ammonia, sulfide and heavy metals) and in particular, nanomaterials, focusing on the mechanism of their inhibition/toxicity. A better understanding of the fundamental mechanisms behind inhibition/toxicity will enhance the wider application of anaerobic digestion.

Contents

Abbreviations: ADM1, Anaerobic Digestion Model No 1; AGS, anaerobic granular sludge; CF, chloroform; CP, monochlorophenol; DCP, dichlorophenol; DCM, dichloromethane; DGGE, denaturing gradient gel electrophoresis; DWCNTs, double walled carbon NTs; EGB, expanded granular sludge bed; EPS, extracellular polymeric substances; FA, free ammonia; FAN, free ammonia nitrogen; IC_{50}, half maximal inhibitory concentration; LCFA, long chain fatty acid; MPB, methane producing bacteria; NP, nanoparticle; NT, nanotube; NZVI, nano zero valent iron; PCE, perchlorethylene; PCP, pentachlorophenol; PEG, polyethylene glycol chain; QSAR, quantitative structure–activity relationship; ROS, reactive oxygen species; SRB, sulfate reducing bacteria; SWNT, single-walled NT; TAN, total ammonia nitrogen; TCE, trichloroethylene; TCP, trichlorophenol; TeCP, tetrachlorophenol; TRFLP, terminal restriction fragment length polymorphism; UASB, upflow anaerobic sludge bed; WWTP, wastewater treatment plant.

* Correspondence to: School of Materials Science & Engineering, Nanyang Technological University N4.1-01-29, 50 Nanyang Drive, Singapore 639798. Tel.: +65 6592 7594; fax: +65 6790 9081.
** Correspondence to: Department of Chemical Engineering, Imperial College London, London SW7 2AZ, UK. Tel.: +44 207 5945591; fax: +44 32 15 317453.
E-mail addresses: wjsteele@ntu.edu.sg (T.W.J. Steele), d.stuckey@imperial.ac.uk (D.C. Stuckey).

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Introduction

Anaerobic digestion can reduce organic pollution from the liquid outputs of homes, industry and agriculture, while potentially offsetting the use of fossil fuels at the same time. In addition, it offers numerous other significant advantages, such as lower energy requirements, and less sludge production compared with traditional aerobic treatment (Chen et al., 2008). Anaerobic digestion consists of a series of microbial processes that convert organics to methane and carbon dioxide, and can take place under psychrophilic (<20 °C), mesophilic (25–40 °C) or thermophilic (50–65 °C) conditions, although biodegradation under mesophilic conditions is most common. It also enables higher loading rates than aerobic treatment, and a greater destruction of pathogens (Ravuri, 2013). Anaerobic digestion can be divided into three major microbial steps, i.e. hydrolysis, acidogenesis/acetogenesis, and methanogenesis represented in Fig. 1 (Amaya et al., 2013). During hydrolysis, a consortia of bacteria break down complex organics (e.g. proteins, cellulose, lignin, and lipids) from the influent into soluble monomers such as amino acids, simple sugars, glycerols, and fatty acids. Hydrolysis of these complex polymers, some of which are insoluble, is catalyzed by extracellular enzymes such as cellulases, proteases, and lipases (Batstone and Jensen, 2011). Acidogenesis includes fermentation and anaerobic oxidation (β-oxidation), which are carried out by fermentative acidogenic and acetogenic bacteria, respectively (Batstone and Jensen, 2011). Fermentative acidogenic bacteria convert sugars, amino acids, and fatty acids to organic acids (e.g. acetic, propionic, formic, lactic, butyric, or succinic acids), alcohols and ketones (e.g. ethanol, methanol, glycerol, and acetone), acetate, carbon dioxide, and hydrogen. Acetate is the major product of carbohydrate fermentation. Acetogenic bacteria convert fatty acids (e.g. long chain fatty acids) and alcohols into acetate, hydrogen, and carbon dioxide, which are used by the methanogens. In the methanogenesis step, acetate, hydrogen, and carbon dioxide are converted into methane by methanogenic microorganisms, which are also classified as archaea composed of both gram-positive and gram-negative bacteria with a wide variety of shapes, e.g., coccoid and bacilli (Michael and Constantinos, 2006). Hydrolysis of insoluble polymers is generally considered as rate-limiting among these successive steps, although with soluble feeds methanogenesis is regarded as the key step in anaerobic digestion (Appels et al., 2008).

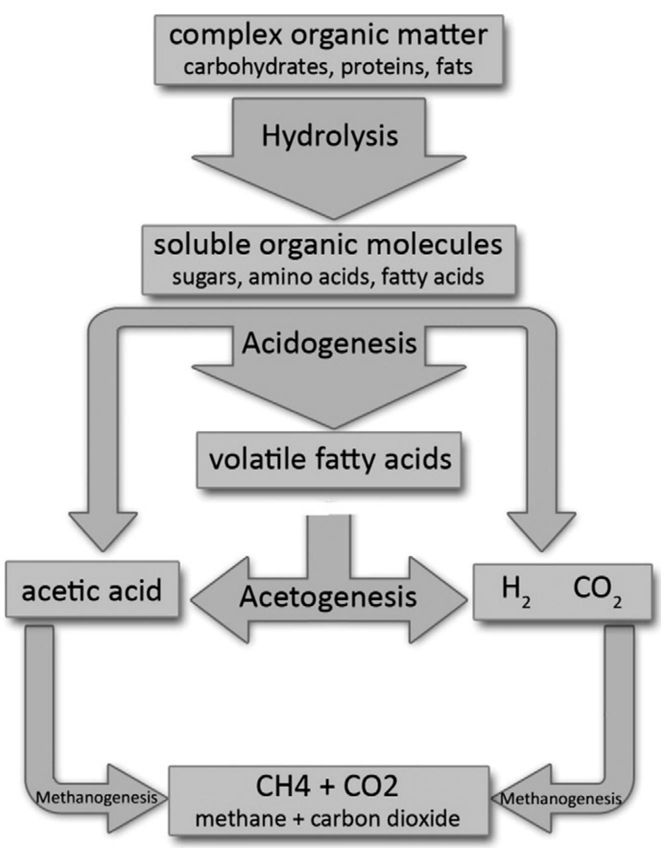

Fig. 1. Schematic representation of the main conversion processes in anaerobic digestion (Amaya et al., 2013) including: 1) hydrolysis, breakdown of complex organics into soluble monomers; 2) acidogenesis, converting small organic molecules into volatile fatty acids; 3) acetogenesis, converting volatile fatty acids into acetic acid, carbon dioxide, and hydrogen; and 4) methanogenesis, consuming hydrogen and converting acetate into methane and carbon dioxide.

One of the main drawbacks to anaerobic digestion is its higher sensitivity to toxicants than aerobic treatment. With the rapid development of nanotechnology, emerging nanomaterials are starting to be used in some industrial products and will inevitably be released into the environment; some nanomaterials have already been found in wastewater treatment plants (WWTPs) and waste sludge (Yang et al., 2013). Hence, more attention is being paid to their impact on the environment (Ju-Nam and Lead, 2008; Yang et al., 2013), and in this review, we will summarize recent work on the effect of nanoparticles and nanotubes on anaerobic digestion and the mechanisms by which they may act. Besides, a wide range of organic chemicals can inhibit anaerobic digestion, including halogenated benzenes (van Beelen and van Vlaardingen, 1994), halogenated phenols (Armenante et al., 1999; Liu et al., 2008), phenol and alkyl phenols (Fedorak and Hrudey, 1984; Levén et al., 2012), halogenated aliphatics (Adamson and Parkin, 1999; Stuckey et al., 1980; van Hylckama Vlieg and Janssen, 2001), and long chain fatty acids (LCFAs) (Hwu et al., 1996; Palatsi et al., 2012). In addition, many inorganic compounds, such as ammonia (Ho and Ho, 2012; Liu and Sung, 2002), sulfide (Cai et al., 2008; Lopes and Lens, 2011) and heavy metals (Altaş, 2009; Oleszkiewicz and Sharma, 1990) are also reported to be inhibitory, and the mechanisms behind inhibition are gradually becoming understood. In this review we have decided to focus on the more common and typical toxicants found in anaerobic membrane bioreactors (Casu et al., 2012; Feng et al., 2013; Stuckey, 2012). This review will also present a detailed comparative summary of research on the inhibition of anaerobic processes by nanomaterials, specific organic (i.e., chlorophenols, halogenated aliphatics and long chain fatty acids) and inorganic toxicants (i.e., ammonia, sulfide and heavy metals), and critically analyze their mechanism of inhibition.

Toxicants

Organic toxicants

Chlorophenols

Chlorophenols are a group of chemicals produced by adding chlorine to phenol, and include monochlorophenols (CPs), dichlorophenols (DCPs), trichlorophenols (TCP), tetrachlorophenols (TeCPs), and pentachlorophenol (PCP). Chlorophenols are used widely as pesticides, herbicides, antiseptics and fungicides as well as preservatives for wood, glue, paint, vegetable fibers and leather. They are found to be highly persistent in both aquatic and terrestrial environments, and are harmful to humans due to their carcinogenicity (Muller and Caillard, 1986). Therefore, chlorophenols are listed as priority pollutants by the U.S. Environmental Protection Agency (U.S. EPA).