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# A Review of Hygienization Technology of Biowastes for Anaerobic Digestion: Effect on Pathogen Inactivation and Methane Production

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This work reviews the application of the hygienization-related technology to the inactivation of pathogens in biowastes prior to anaerobic digestion. First, the paper focused on the existing thermal pasteurization from the perspectives of the worldwide regulations and its energy consumption in biogas plants. In addition, the study attention was attributed to the emerging alternative pasteurization technologies (i.e. Pulsed Electric Fields, High Hydrostatic Pressure, Power Ultrasound, Microwaves and chemical pretreatment). These technologies have been developed and well-studied for food-processing industries. Finally, the effect of these technologies, either traditional thermal treatment or emerging non-thermal treatment, on the methane potential of biowastes was discussed.

## 1. Introduction

Thermal pasteurization has been a major solution to the pathogen inactivation in the food-processing industries (Brennan and Grandison, 2012). This thermal technology has also been borrowed by numerous countries for the purpose of the hygienization (HYG) of certain biowastes that present a potential source of biological risks to public and animal health, which covers a variety of municipal solid wastes (MSW), agricultural waste (AW), animal by-products (ABP) and waste activated sludge (WAS). It is a common practice that the biowastes, rich in organic matters, are treated via biological transformation like composting and anaerobic digestion (AD). Anaerobic digestion is a transformation of organic matters, under anaerobic conditions and by means of fermentative microbiological activities, into biogas that serves as a source of renewable energy in a biogas plant (BGP) (Guarino et al., 2016). The thermal hygienization of bio-wastes before entering AD units remains unclear concerning its treatment efficiency, energy consumption and the impact on the biogas yield of the biowastes treated. The major interest of BGPs is the maximization of the energy recovery of biogas from the wastes to make financial profits and to reduce carbon footprint. Therefore, the heat dedicated to the thermal hygienization may bring negative effect when realizing these economic and environmental goals.
However, many non-thermal pathogen inactivation technologies other than thermal pasteurization have been developed for food-processing industries in recent decades, chiefly for the conservation of food quality and the reduction of energy consumption during the treatment. Electrical pretreatment causes the electroporation on the cellular membrane of microorganisms that are inactivated after a number of pulses during very short time (Zhang et al., 1995). High Hydrostatic Pressure (HHP) can induce a phase transition of the lipid bilayers of pathogens under the intensive pressurization (Martín et al., 2002). Power Ultrasound (PUS) creates cavitation to shock and kill bacteria (Piyasena et al., 2003). Microwaves (MW) give rise to a volume heating of the products and bring about the thermal pretreatment (Tyagi and Lo, 2013). Acid or alkali pretreatment stresses the pathogens by modifying their living conditions. These pretreatment technologies could be a future research focus for the hygienization of biowastes (van Fana et al., 2017). This paper contributes to a comprehensive review of the existing thermal pasteurization from the perspectives of the worldwide regulations and its energy consumption. The work also reviews the application of the emerging alternative pasteurization technologies on the biowastes. Besides, the effect of these technologies on the methane potential of the biowastes was discussed.

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## 2. Thermal hygienization

### 2.1 Worldwide regulations on hygienization of biowastes

Many countries and authorities impose imperatively, prior to the transformation units, a thermal pasteurisation unit of biowastes. The European Union (EU) Regulation No 142/2011 demands that the ABP and the derived products (particle size < 12 mm) should be maintained at 70 °C for one hour without interruption before the introduction into anaerobic digesters (European Commission, 2011). Alternatively, the EU member states are authorized to propose their own hygienization process on condition that the treatment efficiency meet the criteria set by the relevant regulation (i.e. a reduction of 5 log10 of *Enterococcus faecalis* or *Salmonella senftenberg* in ABP). The hygienization parameters are usually regulated depending on the AD operational temperature, namely the mesophilic AD (35 - 40 °C, MAD) or thermophilic AD (> 50 °C, TAD). Austria, Germany proposed a hygienization of wastes at 70 °C for 1 h and 0.5 h prior to MAD and TAD respectively (Colleran, 2000) while in Denmark it was modified as 1.5 h and 1 h at 65 °C for MAD and TAD (Bendixen, 1999). Sweden uses a hygienization step combined in a TAD digester with a minimum retention time for 10 h at 52 °C (Grim et al., 2015). In the United States, instead of the federal government, it is the member states who act to manage the hygienization of ABP. However, the hygienization of WAS (bio-solids) is regulated on a federal level by US EPA who proposes a categorization of sewage sludge into four groups and different Time-Temperature regime applies depending on the category of WAS (US EPA, 2003). In China, the hygienization of biowastes is integrated into the major transformation units (like AD or composting facilities) with the minimum temperature and retention time specified (Ministry of Health of China, 2013).
A summary of the operational parameters of the hygienization of biowastes regulated by different countries is presented in Figure 1. In order to compare the efficiency of these processes with various parameters, a normalised parameter, Pasteurisation value (F-value), was calculated for each process. F-value represents the treatment time required to obtain, at a reference temperature, the same pasteurisation performance as that obtained at a given temperature. The formula to calculate F-value is available in Eq(1).

$$\text{F - value} = \int_0^t 10^{\frac{T - T_{ref}}{z}} dt \quad (1)$$

where F is the Pasteurisation value (min); t is the treatment time (min); T is the given temperature (°C); $T_{ref}$ is the reference temperature (here $T_{ref}$ = 70 °C); z is the temperature rise required for one log10 reduction of pathogen's decimal reduction time (here z = 7 °C for *Enterococcus faecalis*). The F-value permits the comparison of the sanitation efficiency at one same reference temperature (e.g., a hygienization of biowaste at 65 °C for 1.5 h followed by a MAD treatment in Denmark is equivalent to an effect of pathogen inactivation at 70 °C for 17.4 min). It can be concluded from the figure that the EU-level hygienization takes more caution than those proposed by its own members and other countries in the world. Some researchers questioned this prudence in terms of its efficiency and validity of the pathogen dynamics of the treatment (Goden et al., 2017).

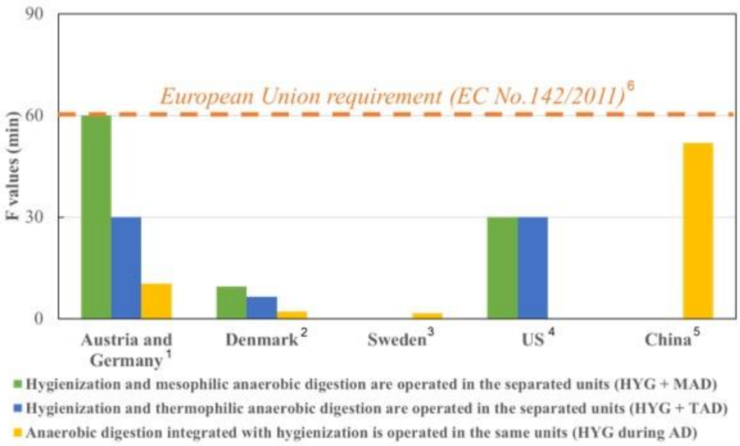


*Figure 1: F-values of the regulation of hygienization for biowastes ([1]Amon and Boxberger, 1999; [2]Bendixen, 1999; [3]Grim et al., 2015; [4]US EPA, 2003; [5]Ministry of Health of China, 2013; [6]European Commission, 2011)*

### 2.2 Heat demand for thermal hygienization process

Table 1 gives a summary of the representation of the heat consumption of the hygienization process in the total heat generation of European BGP. The hygienization of EU scenario (70 °C, 1 h) represents around 6 - 19 % of the total heat production in the BGP in Finland, Germany, Sweden and UK. It required much more in one Irish BGP (30 - 57 %) and this could be explained by the fact that the main feedstock of this BGP was the animal slurry that contained more water content (Coultry et al., 2013). This resulted in a stronger thermal inertia of the substrates, thus requiring more heat than usual. Therefore, the efficiency improvement of the hygienization process can favor the energy production, enlarge the eco-benefit and increase the financial interests for BGP.

*Table 1: Summary of representation of the heat demand of hygienization process in the total heat production of BGP (* considering the heat consumption of whole AD units) ([7]Berglund and Börjesson, 2006; [8]Coultry et al., 2013; [9] Pöschl et al., 2010; [10]Whiting and Azapagic, 2014; [11] Grim et al., 2015)*

| Country of the BGP | Treatment capacity ($kt\cdot y^{-1}$) | Substrates | Operational Parameters of HYG | AD process | Q required by HYG / Q generated by biogas |
|---|---|---|---|---|---|
| Sweden [*,7] | 20 - 60 | AW, crops, WAS, MSW | 70 °C, 1 h | MAD | 6 - 17 % |
| Germany [8] | 10 - 20 | AW, crops, MSW | 70 °C, 1 h | MAD | 10 - 15 % |
| Ireland [9] | 10.7 | Slurry 70 %, AW 30 % | 70 °C, 1 h | MAD | 30 - 57 % |
| UK [*,10] | 5.1 | Slurry 50 %, AW 50 % | 70 °C, 1 h | MAD | 17 % |
| Sweden [11] | 25.2 | MSW 83 %, ABP 18 % | 52 °C, 10 h | TAD | 9 % |

### 2.3 Enhancement of methane potential by thermal hygienization

Thermal hygienization is often performed prior to the AD process. To some extent, it serves as a mild thermal pretreatment. There have been many studies reporting that this thermal pretreatment enhanced the bio-methane potential (BMP) of the biowastes like WAS and ABP. Nevertheless, the results are not always positive when it comes to the digestive tract content, the grease trap sludge (Luste et al., 2009), the primary sludge and the digested WAS (Nazari et al., 2017), the slaughterhouse by-products (Hejnfelt and Angelidaki, 2009), the codigestion of slaughterhouse waste with food waste (Grim et al., 2015), and the dewatered manure (Rafique et al., 2010).

*Table 2: Literature review of mild thermal pretreatment related to methane yield enhancement of biowastes*

| Authors, year | Operational condition | Origin of the substrates | AD process | BMP enhancement |
|---|---|---|---|---|
| Edström et al., 2003 | 70 °C, 1 h | ABP | MAD | +400 % |
| Gavala et al., 2003 | 70 °C, 4 - 7 d | Primary sludge | TAD | from +80 % to +86 % |
| | 70 °C, 1 - 7 d | Secondary WAS | MAD | from +20 % to +26 % |
| Climent et al., 2007 | 70 °C, 0.3 - 3 d | Secondary WAS | TAD | +50 % |
| Luste et al., 2009 | 70 °C, 1 h | Digestive tract content | MAD | −23 % |
| | 70 °C, 1 h | Drumsieve waste | MAD | +48 % |
| | 70 °C, 1 h | Air flotation ABP sludge | MAD | +5.9 % |
| | 70 °C, 1 h | Grease trap sludge | MAD | −6.7 % |
| Hejnfelt and Angelidaki, 2009 | 70 °C, 1 h | Slaughterhouse ABP | TAD/MAD | no sig. difference |
| Luste and Luostarinen, 2010 | 70 °C, 1 h | ABP and WAS | MAD | +13 % |
| Rafique et al., 2010 | 50 - 70 °C, 1 h | Dewatered pig manure | MAD | no sig. difference |
| Luste and Luostarinen, 2011 | 70 °C, 1 h | Cattle slurry | MAD | +33 % |
| Rodríguez-Abalde et al., 2011 | 70 °C, 1 h | Piggery ABP | MAD | +52 % |
| | | Poultry ABP | MAD | +4.3 % |
| Luste et al., 2012 | 70 °C, 1 h | Cattle slurry | MAD | +20 % |
| Yan et al. 2013 | 50 - 100 °C, 0.5 h | Dewatered WAS | MAD | from +272 % to +684 % |
| Grim et al., 2015 | 70 °C, 1 h | Slaughterhouse waste | TAD | no sig. difference |
| Nazari et al., 2017 | 80 °C, 5 h | Various sewage sludge | MAD | from −33 % to +4.6 % |

Table 2 presents a literature review of the impact of mild thermal pretreatment (whose treatment temperatures were inferior to 100 °C, serving as a hygienization step) on the methane production of various biowastes. It is interesting to note that besides the short-term thermal pretreatment (for hours), longer pretreatment time was also studied in order to have a more comprehensive knowledge about its effect on AD methane production (Climent et al., 2007). This long-term mild thermal pretreatment (for days) was reported to promote cell wall breaking of the substrates (Yao et al., 2016).

## 3. Alternative pasteurization technology

Many alternative non-thermal pasteurization technologies are available nowadays in food-processing industries, for example Pulsed Electric Fields (PEF), High Hydrostatic Pressure (HHP), Power Ultrasound (PUS), Microwaves (MW) and chemical pretreatment by acid and alkali.
Numerous studies concerning the positive impact of these technologies on the dewaterbility and on the methane potential enhancement of sewage sludge were conducted (Zhen et al., 2017). A methane production surplus of 33 - 250 %, 10 - 115 %, 9 - 138 %, 20 - 106 % and 1.5 - 145 % was achieved for electro-technology, HHP, PUS, MW and chemical treatment respectively (Carrère et al., 2010). In addition, several studies payed attention to the pathogen inactivation and BMP enhancement of biowastes, as resumed in Table 3. The specific energy input or the chemical dose of the pretreatment was extracted or calculated from the original papers if available.

*Table 3 Literature review of the application of the emerging hygienization technology to various biowastes for pathogen inactivation and BMP enhancement*

| Method | Authors, year | Operational parameters | Type of biowaste | Reduction of the pathogens and BMP enhancement |
|---|---|---|---|---|
| PEF | Keles et al., 2010 | 50 Hz, 0.6 - 1.2kV·cm$^{-1}$ | WAS | 1.4 log10 of *Salmonella* spp. |
| MW | Pino-Jelcic et al., 2006 | 1 kW, 2450 MHz, 110 s | Primary sludge<br>WAS | 4.2 log10 of Fecal coliforms<br>2.0 log10 of *Salmonella* spp. |
| | Hong et al., 2004 | 7.27 kJ·g TS$^{-1}$, 85 °C | Primary sludge | 6.8 log10 of Fecal coliform |
| | | 11.4 kJ·g TS$^{-1}$, 85 °C | WAS | 6.5 log10 of Fecal coliform |
| | | 10.1 kJ·g TS$^{-1}$, 65 °C | AD sludge | 5.6 log10 of Fecal coliform |
| | Hong et al., 2006 | 4.86 kJ·g TS$^{-1}$, 65 °C | Primary sludge | ~5.6 log10 of Fecal coliform |
| | | 7.60 kJ·g TS$^{-1}$, 65 °C | WAS | ~5.4 log10 of Fecal coliform |
| | | 10.1 kJ·g TS$^{-1}$, 65 °C | AD sludge | ~3.5 log10 of Fecal coliform |
| PUS | Chu et al., 2001 | 20 kHz, 0.1 - 0.3 W·mL$^{-1}$<br>120 min | WAS | 3 log10 of Total coliform<br>2.4 log10 of heterotrophs |
| | Ruiz-Hernando et al., 2014 | 5 - 27 kJ·g TS$^{-1}$ | WAS | 4 log10 of *Escherichia coli*<br>+10 % $CH_4$ production |
| Alkali | Ruiz-Hernando et al., 2014 | 35 - 157 g NaOH·kg TS$^{-1}$<br>24 h | WAS | 4 log of *Escherichia coli*<br>+30 % $CH_4$ production |
| Coupled | Jin, 2010 | 70 g NaOH·kg TS$^{-1}$<br>+ MW, 120 °C, 30 min | Dairy manure | ~+50 % $CH_4$ production |
| | | 70 g CaO·kg TS$^{-1}$<br>+ MW, 120 °C, 30 min | Dairy manure | ~+50 % $CH_4$ production |
| | | 2 % (v/v) $H_2SO_4$<br>+ MW, 120 °C, 30 min | Dairy manure | no sig. $CH_4$ enhancement |
| | | 0.74 % (v/v) HCl<br>+ MW, 120 °C, 30 min | Dairy manure | ~+50 % $CH_4$ production |

While increasing research focus was given to the WAS, scarce studies are available concerning the effect of these novel technologies on either the effect on pathogen reduction or methane potential enhancement of the ABP in a systematic way.

## 4. Conclusions

Worldwide regulations on the hygienization of biowastes focus on a mild thermal pretreatment prior to the AD process. European Union proposes the strictest sanitary rules (70 °C for 1 h) as compared to other countries. This thermal hygienization accounts for around 6 - 19 % of the total energy production in European biogas plants. The hygienization, serving as a mild thermal pretreatment, might give rise to a positive impact on the methane yield of the majority of the AD feedstock, while no effect or negative effect could also be seen for slaughterhouse by-products and several primary WAS. The application of emerging technologies on the WAS has been systematically studied in terms of its effects on the dewaterbility, on the methane potential enhancement and on the pathogen inactivation. Nevertheless, these effects on the ABP and other biowastes are insufficient. The energy consumption (considering the effect of BMP enhancement) and the related environmental impact (life cycle assessment) are not well studied either. These could be future research focuses and improve a cleaner energy production of anaerobic digestion.

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**References**

Amon T., Boxberger J., 1999, Organic wastes for codigestion in agricultural biogas plants: guidelines and legal conditions in Austria, Presented at the Proceedings of the IEA BioEnergy workshop: Hygienic and environmental aspects of anaerobic digestion: legislation and experiences in Europe, Stuttgart, Germany.

Bendixen H.J., 1999, Hygienic Safety–Results of scientific investigations in Denmark (Sanitation requirements in Danish biogas plants), Presented at IEA BioEnergy Workshop: Hygienic and environmental aspects of AD: Legislation and experiences in Europe, Stuttgart, Germany.

Berglund M., Börjesson P., 2006, Assessment of energy performance in the life-cycle of biogas production, Biomass and Bioenergy, 30, 254–266.

Brennan J.G. (Ed), 2012, Food Processing Handbook, John Wiley Sons, Berks, UK.

Chu C.P., Chang B.V., Liao G.S., Jean D.S., Lee D.J., 2001, Observations on changes in ultrasonically treated waste-activated sludge, Water Research, 35, 1038–1046.

Carrère H., Dumas C., Battimelli A., Batstone D.J., Delgenès J.P., Steyer J.P., Ferrer I., 2010, Pretreatment methods to improve sludge anaerobic degradability: A review, Journal of Hazardous Materials, 183, 1–15.

Climent M., Ferrer I., Baeza M., del M., Artola A., Vázquez F., Font X., 2007, Effects of thermal and mechanical pretreatments of secondary sludge on biogas production under thermophilic conditions, Chemical Engineering Journal, 133, 335–342.

Coelho N.M.G., Droste R.L., Kennedy K.J., 2011, Evaluation of continuous mesophilic thermophilic and temperature phased anaerobic digestion of microwaved activated sludge, Water Research, 45, 2822–2834.

Colleran E., 2000, Hygienic and sanitation requirements in biogas plants treating animal manures or mixtures of manures and other organic wastes, Presented at Anaerobic Digestion: Making Energy and Solving Modern Waste Problem, 77–86.

Coultry J., Walsh E., McDonnell K.P., 2013, Energy and economic implications of anaerobic digestion pasteurisation regulations in Ireland, Energy, 60, 125–128.

Edström M., Nordberg A., Thyselius L., 2003, Anaerobic Treatment of Animal Byproducts from Slaughterhouses at Laboratory and Pilot Scale, Applied Biochemistry and Biotechnology, 109, 127–138.

European Commission, 2011, Commission Regulation (EU) No 142/2011 of 25 February 2011 implementing Regulation (EC) No 1069/2009 of the European Parliament and of the Council laying down health rules as regards animal by-products and derived products not intended for human consumption and implementing Council Directive 97/78/EC as regards certain samples and items exempt from veterinary checks at the border under that Directive, Official Journal of the European Union, 54.

Gavala H.N., Yenal U., Skiadas I.V., Westermann P., Ahring B.K., 2003, Mesophilic and thermophilic anaerobic digestion of primary and secondary sludge, Effect of pre-treatment at elevated temperature, Water Research, 37, 4561–4572.

Goden J.J., Wery N., Bernet N., 2017, Pathogen decay or growth in anaerobic digestion: a question with no possible answer? Elements of understanding for non-microbiologists, Presented at the 15th IWA International Conference on Anaerobic Digestion (Poster No D2), Beijing, China.

Grim J., Malmros P., Schnürer A., Nordberg Å., 2015, Comparison of pasteurization and integrated thermophilic sanitation at a full-scale biogas plant – Heat demand and biogas production, Energy, 79, 419–427.

Guarino G., Carotenuto C., di Cristofaro F., Papa S., Morrone B., Minale M., 2016, Does the C/N ratio really affect the Bio-methane Yield? A three years investigation of Buffalo Manure Digestion, Chemical Engineering Transactions, 49, 463–468.

Hejnfelt A., Angelidaki I., 2009, Anaerobic digestion of slaughterhouse by-products, Biomass and bioenergy, 33, 1046–1054.

Hong S.M., Park J.K., Lee Y.O., 2004, Mechanisms of microwave irradiation involved in the destruction of fecal coliforms from biosolids, Water Research, 38, 1615–1625.

Hong S.M., Park J.K., Teeradej N., Lee Y.O., Cho Y.K., Park C.H., 2006, Pretreatment of Sludge with Microwaves for Pathogen Destruction and Improved Anaerobic Digestion Performance, Water Environment Research, 78, 76–83.

Jin Y., 2010, Microwave-based Pretreatment Pathogen Fate and Microbial Population in a Dairy Manure Treatment System, PhD Thesis, Virginia Polytechnic, Virginia, USA.

Keles C., Icemer G.T., Ozen S., 2010, Inactivation of Salmonella spp. by low-frequency electric fields in sewage sludge, Journal of Civil and Environmental Engineering, 10, 13–18.

Luste S., Heinonen-Tanski H., Luostarinen S., 2012, Co-digestion of dairy cattle slurry and industrial meat-processing by-products – Effect of ultrasound and hygienization pre-treatments, Bioresource Technology, 104, 195–201.

Luste S., Luostarinen S., 2010, Anaerobic co-digestion of meat-processing by-products and sewage sludge – Effect of hygienization and organic loading rate, Bioresource Technology, 101, 2657–2664.

Luste S., Luostarinen S., 2011, Enhanced methane production from ultrasound pre-treated and hygienized dairy cattle slurry, Waste Management, 31, 2174–2179.

Luste S., Luostarinen S., Sillanpää M., 2009, Effect of pre-treatments on hydrolysis and methane production potentials of by-products from meat-processing industry, Journal of Hazardous Materials, 164, 247–255.

Martín M.F.S., Barbosa-Cánovas G.V., Swanson B.G., 2002, Food Processing by High Hydrostatic Pressure, Critical Reviews in Food Science and Nutrition, 42, 627–645.

Ministry of Health of China, 2013, Hygienic requirements for harmless disposal of night soil.

Nazari L., Yuan Z., Santoro D., Sarathy S., Ho D., Batstone D., Xu C., Ray M.B., 2017, Low-temperature thermal pre-treatment of municipal wastewater sludge: Process optimization and effects on solubilization and anaerobic degradation, Water Research, 113, 111–123.

Pino-Jelcic S.A., Hong S.M., Park J.K., 2006, Enhanced Anaerobic Biodegradability and Inactivation of Fecal Coliforms and Salmonella spp. in Wastewater Sludge by Using Microwaves, Water Environment Research, 78, 209–216.

Piyasena P., Mohareb E., McKellar R.C., 2003, Inactivation of microbes using ultrasound: a review, International Journal of Food Microbiology, 87, 207–216.

Pöschl M., Ward S., Owende P., 2010, Evaluation of energy efficiency of various biogas production and utilization pathways, Applied Energy, 87, 3305–3321.

Rafique R., Poulsen T.G., Nizami A.S., Asam Z.Z., Murphy J.D., Kiely G., 2010, Effect of thermal chemical and thermo-chemical pre-treatments to enhance methane production, Energy, 35, 4556–4561.

Rodríguez-Abalde A., Fernández B., Silvestre G., Flotats X., 2011, Effects of thermal pre-treatments on solid slaughterhouse waste methane potential, Waste Management, 31, 1488–1493.

Ruiz-Hernando M., Martín-Díaz J., Labanda J., Mata-Alvarez J., Llorens J., Lucena F., Astals S, 2014, Effect of ultrasound low-temperature thermal and alkali pre-treatments on waste activated sludge rheology hygienization and methane potential, Water Research, 61, 119–129.

Tyagi V.K., Lo S.L., 2013, Microwave irradiation: A sustainable way for sludge treatment and resource recovery. Renewable and Sustainable, Energy Reviews, 18, 288–305.

US EPA, 2003, Environmental regulation and technology control of pathogens and vector attraction in sewage sludge, Under No. 40 CFR Part 503.

Fan Y. V., Lee C.T., Klemeš J.J., 2017, The Update of Anaerobic Digestion and the Environment Impact Assessments Research, Chemical Engineering Transactions, 57, 7–12.

Whiting A., Azapagic A., 2014, Life cycle environmental impacts of generating electricity and heat from biogas produced by anaerobic digestion, Energy, 70, 181–193.

Yan Y., Chen H., Xu W., He Q., Zhou Q., 2013, Enhancement of biochemical methane potential from excess sludge with low organic content by mild thermal pretreatment, Biochemical Engineering Journal, 70, 127–134.

Yao Y., Huang Y., Hong, F., 2016, The influence of sludge concentration on its thermophilic anaerobic digestion performance based on low temperature thermal hydrolysis pretreatment, Procedia Environmental Sciences, 31, 114-152.

Zhang Q., Barbosa-Cánovas G.V., Swanson B.G., 1995, Engineering aspects of pulsed electric field pasteurization, Journal of Food Engineering, 25, 261–281.

Zhen G., Lu X., Kato H., Zhao Y., Li Y.Y., 2017, Overview of pretreatment strategies for enhancing sewage sludge disintegration and subsequent anaerobic digestion: Current advances full-scale application and future perspectives, Renewable and Sustainable Energy Reviews, 69(Supplement C), 559–577.