Global J. Environ. Sci. Manage. 5(1): 119-138, Winter 2019

Global Journal of Environmental Science and Management
(GJESM)

Homepage: https://www.gjesm.net/

REVIEW PAPER

# Expanded granular sludge bed bioreactor in wastewater treatment

**A. Cruz-Salomón[1,2,*], E. Ríos-Valdovinos[1], F. Pola-Albores[1], S. Lagunas-Rivera[3], R. Meza-Gordillo[2], V.M. Ruíz-Valdiviezo[2], K.C. Cruz-Salomón[2]**

*[1]Instituto de Investigación e Innovación en Energías Renovables, Universidad de Ciencias y Artes de Chiapas, Tuxtla Gutiérrez, Chiapas, México*
*[2]Departamento de Ingeniería Química y Bioquímica, Tecnológico Nacional de México/Instituto Tecnológico de Tuxtla Gutiérrez, Tuxtla Gutiérrez, Chiapas, México*
*[3]Conacyt, Departamento de Química, Universidad de Guanajuato, Guanajuato, Guanajuato, México*

**ARTICLE INFO**

***Article History:***
Received 17 September 2018
Revised 24 November 2018
Accepted 25 December 2018

***Keywords:***
Anaerobic bioreactor
Expanded granular sludge bed (EGSB)
Hydrodynamics
Mathematical model
Operating conditions
Wastewater treatment

**ABSTRACT**

The expanded granular sludge bed bioreactor appears today as a cheap, robust and more popular technology because it operates using a fluidized bed, which allows increasing in organic load and in cell retention times, generating higher treatment efficiencies (up to 95 %) and renewable energy (i.e., biogas, biomethane, and biohydrogen). Nevertheless, the efficiency of this bioreactor mainly depends on the operating conditions. Thus, the content presented in this review paper focuses on the analysis of the operating conditions and performance of expanded granular sludge bed bioreactor for treating different types of industrial, agro-industrial and domestic wastewaters (e.g., agro-food, beverage, alcohol distillery, tannery, slaughterhouse, chemical, pharmaceutical, municipal sewage, among others). Because of this reason, this study aimed to analyze the operating conditions and type of substrate, which has been used in these bioreactors to improve future research to wastewater treatment and renewable energy production. According to the review, it is concluded that the EGSB bioreactor is a novel sustainable alternative to treat different types of wastewaters and consequently change the paradigm of wastewater management from “treatment and disposal” to “beneficial use” as well as “profitable effort”.

DOI: 10.22034/gjesm.2019.01.10



## INTRODUCTION

Water is an essential natural resource for human activity that is directly related to economic aspects, as well as health and safety. Nowadays, the global water scarcity, the growth of the world population and escalating crisis of water pollution, it is beginning to take its toll in many regions. Water resources are facing increasingly deficient, and the value of environment in the world is persistently becoming worse in most regions (Cruz-Salomón, 2018). Therefore, the development of sustainable, reliable and low-cost technologies is necessary for the treatment of wastewater. Due to this problem, expanded granular sludge bed (EGSB) bioreactor has attracted many researchers, because it has several advantages like design simplicity, usage of unsophisticated equipment, low anaerobic granular sludge (AGS)

*Corresponding Author:
Email: *dr.abumale@gmail.com*
Tel.: +961 236 8925
Fax: +961 615 1687

Note: Discussion period for this manuscript open until April 1, 2019 on GJESM website at the “Show Article.

production, high treatment efficiency, low operating costs and its potential to generate renewable energy (like biogas, biomethane or biohydrogen) have turned to this bioreactor into a sustainable alternative to mitigate the crisis of water pollution. The EGSB bioreactor (novel variation of the upflow anaerobic sludge blanket (UASB) bioreactor) was developed in the Netherlands in the mid-1980s to increase AGS/wastewater contact and contribute to the reduction of the presence of dead zones, a preferential flow and short-circuits that can be carried out in the UASB bioreactor, so some studies have shown that the internal mixing in a pilot scale UASB bioreactor was not optimal (de Man *et al.,* 1986), causing the decline in the treatment efficiency (Kato *et al.,* 2003; Fuentes *et al.*, 2011). In order to solve this problem (internal mixing between the AGS and wastewater) and take advantage of the entire bioreactor volume efficiently, a better influent distribution was required. Consequently, various alternatives were evaluated, it being the use of effluent recirculation combined with taller bioreactors (or a high height/diameter ratio), gave rise to the EGSB bioreactor (van der Last and Lettinga, 1992; van Lier *et al.,* 2001; Chan *et al.,* 2009). This bioreactor (Fig. 1) compared with conventional UASB bioreactor (second-generation) was classified as a third-generation anaerobic system, there are two ways to retain microorganism through self-immobilization or in granular sludge with good settling properties, which allows it to generate high upflow velocities ($V_{up}$) for the liquid and gas, these high liquid rates, together with the lifting action of gas development in the bed which leads to a (modest) expansion of the sludge bed. Consequently, an excellent contact between AGS and wastewater prevails in the bioreactor, leading to operate at ultra-high load. As a result of the biogas turbulence that accumulates from the bottom to top reducing the dead zones (Zoutberg and de Been, 1997; von Sperling and Chernicharo, 2005; van Lier *et al.,* 2015). Interestingly when using EGSB bioreactor, many types of wastewater can be treated, but cannot be treated using conventional UASB bioreactor such as:

1) Effluents containing recalcitrant or highly toxicant but are biodegradable compounds, like pesticide, methanol, phenol, and formaldehyde (van Lier et *al.,* 2015).

2) Cold (even < 10 °C) and dilute (chemical oxygen demand (COD) <1 g/L) effluents, i.e., when biogas production is meager, and there is not biogas mixing (Rebac *et al.,* 1998).

3) Effluents from the textile industry, which contain dyes and other toxic auxiliary compounds (e.g., $Na_2SO_4$, phenols, and chlorinated solvents) can be treated and successfully converted into renewable energy without inhibitory effects on the AGS (Frijters *et al.,* 2006).

4) Effluents containing fats and long chain fatty acids. Fatty effluents generally lead to (sludge bed) clogging problems in UASB bioreactor (Rinzema *et al.,* 1993).

5) Effluents with foaming problems in UASB bioreactor (e.g., fats, lipids, proteins) (van Lier *et al.,* 2001).

Nevertheless, due to the bioreactor´s short existence within the market, there is only a small number of publications that disclose the research of this technology. Which allows to conclude the

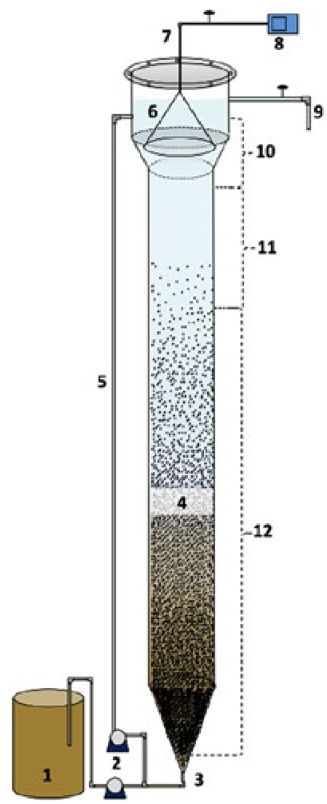


Fig. 1: The schematic diagram of an EGSB bioreactor. (1) Feed tank, (2) Peristaltic pump, (3) Influent, (4) EGSB bioreactor, (5) Recirculation, (6) Bell separation, (7) Biogas outlet, (8) Gas flow-meter, (9) Effluent, (10) Three-phase separator zone or Settling zone, (11) Transition zone, (12) Digestion zone.

importance of the necessity to perform an analysis of the main operating conditions of this bioreactor (like organic loading rate (OLR), hydraulic retention time (HRT), $V_{up}$, diameter/height ratio, bed expansion, temperature, pH and type of substrate); since due to these variables affect its efficiency and performance (organic matter removal efficiencies and biogas production). Because of this reason, this study aimed to analyze the operating conditions and type of substrate, which has been used in these bioreactors to improve future research to wastewater treatment and renewable energy production.

This study has been carried out in the Institute for Research and Innovation in Renewal Energies of the University of Sciences and Arts of Chiapas, in collaboration with the National Institute of Technology of Mexico and the University of Guanajuato in 2018.

*Characteristics of EGSB bioreactor*

The EGSB bioreactor combines characteristics of UASB bioreactor and fluidized bed bioreactor (FBR) (Frankin *et al.,* 1992; Zoutberg and Frankin, 1996). It is composed by an expanded bed (sludge bed heights up to 60 % of the total height of the bioreactor) and a GLS (Gas-Liquid-Solid) three-phase separator zone (also called settling zone) which allows to separate the treated wastewater from AGS and gas; this zone is located in the upper part of the bioreactor and is characterized for having a diameter up to 3 times larger than in the digestion zone. The digestion zone (expanded bed of the bioreactor) is the area where the chemical transformation of the presents pollutants in the wastewater is carried out (removal up to 90 % of the contaminants present in the liquid phase) with the assistance of the microbial consortiums presents in the AGS. On the other hand, one feature that makes them differ from the UASB bioreactors, is the presence of recirculation of the medium, which allows assistance in diluting biodegradable inhibitory and toxic substances, initially present in the wastewater (Monsanto *et al.,* 2014; Teixeira-Correia *et al.,* 2014; Londoño and Peñuela, 2015). Therefore, by adding recirculation, the EGSB bioreactor can be used under difficult conditions (inhibitory or toxic substances), including wastewater generated by the chemical and pharmaceutical industry. This bioreactor has higher height/diameter ratio (10/1 up to 25/1), allowing the application of higher upflow velocities, reaching values of 6 m/h or even higher (up to 30 m/h) for liquid and 7 m/h for gases. These hydraulic characteristics allow the construction of tall and slender bioreactors with a scarce occupation of space. Industrially, the EGSB bioreactors have heights in the range between 7 to 24 m (Teixeira-Correia *et al.,* 2014). Due to the application of higher velocities in the EGSB bioreactors, there is a more significant expansion of the medium, providing a greater contact between AGS to wastewater, which allows it to operate at ultra-high OLR up to 40 kg COD/$m^3$d, low HRT from 0.2 to 2 days for low-strength wastewater (in such a situation effluent recirculation is not needed), up to 10 days for high-strength wastewater (like vinasse, palm oil mill effluent (POME), coffee processing wastewater (CPWW), soft drink industry wastewater (SDIW), among others) and start-up times between 30 to 60 days (Lillo-Cámpora, 2017). Also, the design of this bioreactor offers maximum efficiency, stability and flexibility to treat various types of wastewater thanks to its external recirculation, a feature that allows efficient internal mixing and optimal contact between AGS to wastewater (Kato *et al.,* 2003; López and Borzacconi, 2011). Thus, besides in which is a completely closed system, with zero emission of odors, this bioreactor has a high potential to generate renewable energy in the form of biogas, biomethane or biohydrogen, which is collected in the head space. The main characteristics of EGSB bioreactors are presented below in Fig. 2. The EGSB bioreactor with high liquid and/or gas upflow rates requires AGS with excellent settling characteristics. The AGS stratification befalls due to the difference in size (diameter around 0.5 to 5 mm) and density among the biofilm particles (Hulshoff Pol *et al.,* 2004). Thicker AGS are generally found at the bottom of the digestion zone, while bare, less dense, and thin AGS remain in the top region of the digestion zone of the bioreactor (Hermanovicz and Ganczarczyk, 1983; Boaventura and Rodrigues, 1988). Particle stratification has been attributed to differences in drag and buoyancy that affect particle terminal settling velocity (Di Felice, 1995). As a result of stratification and size distribution, the biodegradation rate, AGS composition, and AGS-specific activity all change at the height of the digestion zone. For instance, the glucotrophic activity in anaerobic EGSB bioreactor decreases along the digestion zone from the bottom to the top, on the contrary to the methanogenic activity that increases at the top of the digestion zone of the bioreactor

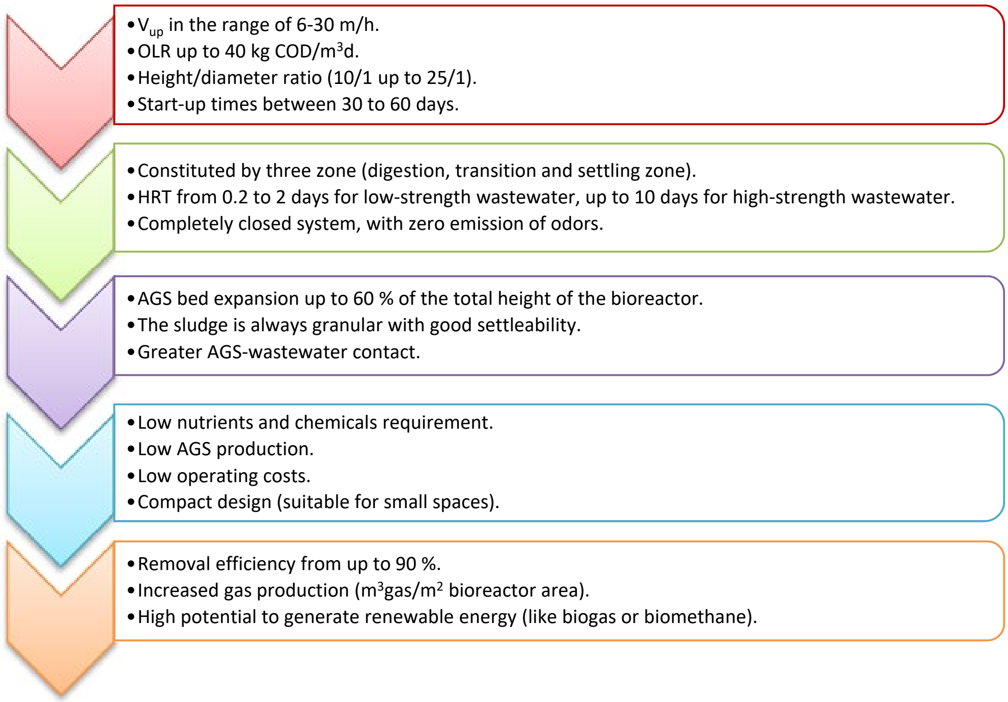


Fig. 2: Main characteristics of EGSB bioreactor

(Buffiere *et al.,* 1998). In the higher portion of the bed, where the thinnest AGS are present, diffusional mass transfer limitations are particularly important which decrease the efficiency of the treatment and the removable energy generation of the bioreactor (Schreyer and Coughlin, 1999; Nicolella *et al.,* 2000).

However, even though the EGSB bioreactor has great virtues, it is not adequate for the removal of suspended solids, particulate, pathogen, nutrient and colloidal organic matter due to the high velocity of the liquid upflow, causing that suspended solids, pathogen, particulate and colloidal are only partially removed since they are not retained by the anaerobic granular sludge bed finally leave the bioreactor together with the effluent (Haandel, 2007); It generates low pathogen (except helminth eggs, which are efficiently captured in the sludge bed) and nutrient (nitrogen and phosphorus) removal. Due to nutrients removal are not complete, therefore a post-treatment is required for compliance with environmental regulations. (Seghezzo *et al.,* 1998; Seghezzo, 2004; Kaviyarasan, 2014). Possible bad odors and abrasion are generated because of the presence of hydrogen sulfide ($H_2S$) which is formed during the anaerobic treatments, especially when the wastewaters have high concentrations of sulfate ($SO_4^{-2}$) in the influent. On the other hand, another difficulty present in this bioreactor are the longs start-up times caused by numerous biological, chemical and physical parameters such as composition and concentration of the wastewater. Also, the capacity of adaptation of the AGS, environmental parameters, operational parameters, geometric configuration, and bioreactor size. In addition, this bioreactor can have problems with biomass retention (Alphenaar, 1994), resulting in granule disintegration, wash-out of hollow granules, the occurrence of fluffy granules, and scaling by inorganic precipitates.

*Factors Influencing bioreactor's Performance*

Many factors which can affect the bioreactor's performance, like the wastewater characteristics, particle size distribution (PSD), acclimatization of AGS, bioreactor configuration, and the operational parameters like HRT, sludge retention time (SRT), $V_{up}$, OLR, and the environmental factors such as temperature and pH (Fig. 3).

*Wastewater characteristics*

The different wastewater (domestic, industrial and agro-industrial) are enormously variable regarding flow and physical-chemical composition, so it is essential to know the type of wastewater that is to be treated in an EGSB bioreactor since due to its characteristics or composition these can affect its performance. As a general rule it is important to know the biodegradability index (biochemical oxygen demand ($BOD_5$)/COD ratio), where it is recommended to have a $BOD_5$/COD> 0.3 (Cruz-Salomón *et al.,* 2017a; Cruz-Salomón, 2018), this secures that more than 30 % of the organic matter present in the wastewater is biodegradable. On the contrary, if the $BOD_5$/COD ratio is lower 0.3, the wastewater is not suitable to use in EGSB bioreactor since the performance would be extremely low. Just as it is essential biodegradability index it is also important to take into account the fats, oil, and grease (FOG)/COD ratio, where it is recommended that it should have a FOG/COD< 0.2 (Cruz-Salomón, 2018), if the FOG/COD ratio is above 0.2, it has a detrimental on a full scale, resulting in biomass washout and therefore low removal efficiency. Other relevant parameters to predict the stability and proper performance of the EGSB bioreactor are the C/N ratio (COD/TKN) (30/1 to 15/1), C/P ratio (130/1 to 60/1) (adapted ratio of the correlation COD vs. TOC) and competitiveness index (COD/$SO_4^{-2}$ ratio). Thus, a high C/N ratio is an indication of the rapid consumption of nitrogen by the microbial population involved in the process and may lead to a slow microbial growth due to subsequent nitrogen deprivation. Low C/N ratios could cause ammonia accumulation, the occurrence of pH values exceeding 8.5, which are toxic to microbial complexes, and consequently decreased the efficiency in the EGSB bioreactor (Cruz-Salomón *et al.,* 2017a). The COD/$SO_4^{-2}$ >10 (Ramos-Vaquerizo *et al.,* 2018) is recommended to avoid the competitiveness generated between methanogenic archaea and sulfate-reducing bacteria in the EGSB bioreactor; otherwise, it will be necessary to dilute the influent to eliminate competition for such microorganisms. On the other hand, it is recommended that the wastewater have a total suspended solids (TSS) concentration < 8 % (Cruz-Salomón, 2018) to ensure the proper functioning of the bioreactor, since the excessive concentration of TSS in the influent can cause inconveniences such as decrease of the working volume of bioreactor, it decreases the useful characteristics of AGS and hence

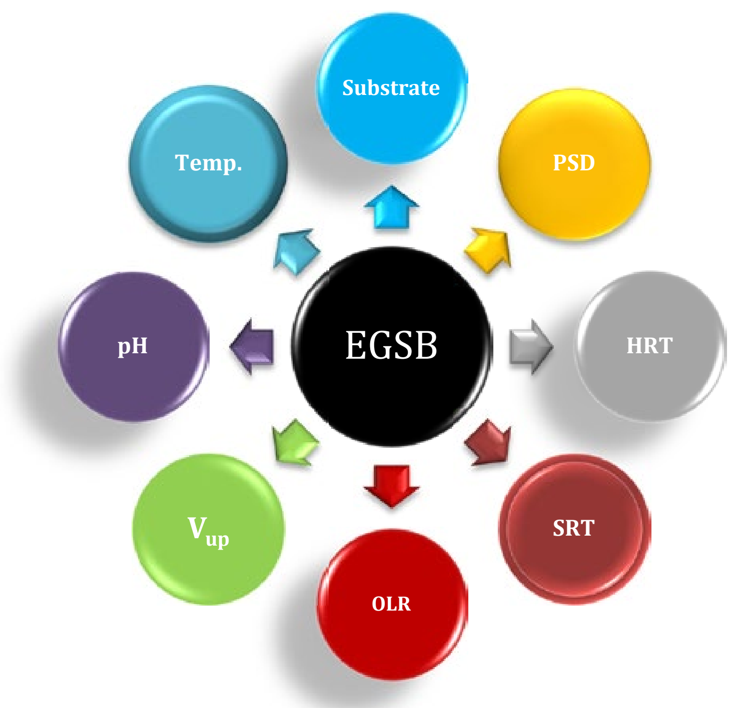


Fig. 3: Factors influencing bioreactor's performance

decreases bioreactor's performance. In addition, the presence of toxicants in the wastewater, such as oxygen (lethal to obligate anaerobes), ammonia, chlorinated hydrocarbons, aromatic hydrocarbons, heavy metals, long-chain fatty acids, and excess volatile fatty acid (VFA) concentrations, among several others, may also result in occasional failures of EGSB bioreactor. The structure of the decision tree to identify the wastewater to suitable for EGSB bioreactor is presented below in Fig. 4.

*Potential of hydrogen (pH)*

The pH of an anaerobic EGSB bioreactor is especially important because it affects the operation of the bioreactor, digestive progress and products directly. Therefore, it is important to maintain an optimum pH range. Many studies have been reported that optimum pH range for anaerobic bioreactors to be 6.7–7.4. (Xing *et al.,* 2009; Mao *et al.,* 2015; Cruz-Salomón *et al.,* 2017b). Because the microorganisms responsible for anaerobic digestion are hydrolytic, acidogenic bacteria and methanogenic archaea. The acid-producing bacteria tolerate a low pH, but the ideal pH range 5-6, while methanogenic archaea may have higher metabolic activity at a pH range 6.7-7.4. Nevertheless, when the pH value in the bioreactor is not maintained in the range of 6-8, the activity of methanogenic archaea is reduced (Kaviyarasan, 2014), and this cause a negative influence in the EGSB bioreactor performance. pH values below 6 (may result from acids production in the acidogenesis) also cause inhibition of the activity of archaea and pH values above 8 (may result from ammonia production during protein degradation) also have an inhibiting effect (Angelidaki and Ahring, 1993; Angelidaki *et al.,* 1993; Chen *et al.,* 2008a; Cruz-Salomón, 2018). In the case of domestic wastewater, pH remains in this range, and the addition of chemical is not required. However, in the case of industrial or agro-industrial wastewaters, depending on their nature, so they need to be conditioned with a chemical like $NaHCO_3$, NaOH, or $Ca(OH)_2$ for acid wastewater or mineral acids for alkaline wastewater.

*Temperature (t)*

Temperature is a factor that plays a key role during the anaerobic process using EGSB technology. It considerably influences the growth and survival of microorganisms. If the temperature is not suitable, some operational aspects could be affected in the bioreactor, such as the conversion, kinetics, stability, effluent quality, and consequently, the efficiency of the organic matter removal and yield renewable energy production (biogas or biomethane) decrease (Sanchez *et al.,* 2001). The anaerobic treatment has been possible in three temperature levels (psychrophilic, mesophilic and thermophilic with optimal temperatures below 20 °C, 25-40 °C and above

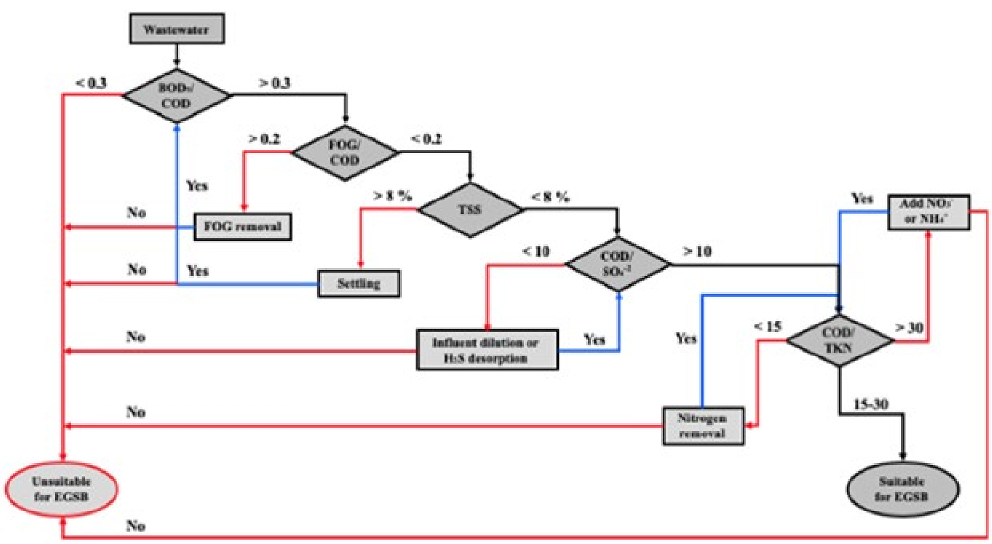


Fig. 4: Structure of the decision tree to identify the wastewater to suitable for EGSB bioreactor

45 °C, respectively). Thus, it has been demonstrated that the efficiency of the elimination of organic matter is correlated with the increase in temperature when psychrophilic, mesophilic and thermophilic conditions were compared (Sanchez *et al.,* 2001; Ahn and Forster, 2002; Kim *et al.,* 2002). This is contrasted with the use of the EGSB bioreactor, which has been operated commonly in the mesophilic range (35 - 37 °C) despite the fact that the temperature of certain wastewater has been warmer or colder. Therefore, the treatment of wastewater at its original temperatures would be beneficial due to the reduction of resources and economic costs (Kettunen and Rintala, 1997; Donoso-Bravo *et al.,* 2009; Cruz-Salomón, 2018). However, due to the improved interaction between the AGS and wastewater, there are reported works of EGSB bioreactors operated at lower temperatures (below 35 °C until 10 °C) with good performance.

*Retention time (RT)*

The RT is the average time in which a particle of fluid remains within a certain volume in a continuous process. It is associated with the rate of microbial growth and may depend on factors such as the temperature, the OLR and the type of wastewater (composition). In this study, two important types of RT were evaluated: The SRT and HRT. The first corresponds to the average time that microorganisms (solids) spend in a bioreactor, and the second corresponds to the residence time of wastewater in the bioreactor (Ekama and Wentzel, 2008; Cruz-Salomón, 2018).

*Sludge retention time (SRT)*

The SRT is an important design and operating parameter that affects the biochemical and physical characteristics of the AGS (Halalsheh *et al.,* 2005). The successful functioning of the EGSB bioreactors depends mainly on the SRT, which is the crucial factor that determines the final amount of hydrolytic and methanogenic microorganisms presents in the EGSB bioreactor under different temperature conditions (Abdelgadir *et al.,* 2014). To retain a sufficient amount of methanogenic microorganisms in the bioreactor biofilm, it is necessary to keep the SRT above the time of duplication of the methanogenic microorganisms. It leads to the formation of AGS with a sufficient level of methanogenic archaea, which are microorganisms with high potential for methane production. In general, the SRT must be maintained 2 to 3 times above the doubling time of the bacteria to maintain the functioning of a stable operating bioreactor. In a review of the literature, the retention time of sludge in anaerobic bioreactors was investigated (Borja *et al.,* 1995, Syutsubo *et al.,* 2008; de la Rubia *et al.,* 2006). However, there are few published reports related to SRT in the EGSB bioreactor system for the treatment of low and high resistance wastewater (Yoochatchaval *et al.,* 2008). The SRT can be calculated using Eq. 1.

$$SRT = \frac{X_{bioreactor} * V_{bioreactor}}{Q_{effl.} * X_{effl.} + Q_{excess-sludge} * X_{excess-sludge}} \quad (1)$$

Where X corresponds to the viable biomass concentration (kg/m$^3$), V is the volume of the bioreactor (m$^3$), and Q is the flow rate (m$^3$/d). Thus, the minimum SRT must always be more than three times the doubling time (Td) of the biomass responsible for the speed limitation step.

*Hydraulic retention time (HRT)*

The HRT (also-called hydraulic residence time) is the average time that fluid (wastewater) remains in a bioreactor. HRT has been one of the most important parameters affecting the design, operational/ investment cost, energy requirement and the performance of the EGSB bioreactor (Cruz-Salomón, 2018). The very long HRT will adversely affect the sludge granulation process in the EGSB bioreactor, and very short HRT is a disadvantage since the biomass can come out with effluent (Kaviyarasan, 2014). To optimize the HRT is necessary to take into account the type of wastewater (composition) and OLR; usually, a few days or weeks are required (Mao *et al.,* 2015). In the case of low-strength wastewater the HRT from 0.2 to 2 days and high-strength wastewater (like industrial or agro-industrial wastewater), the HRT can be up to 10 days (Cruz- Salomón *et al.,* 2018). The HRT can be calculated using Eq. 2.

$$HRT = \frac{V}{Q} \quad (2)$$

Where HRT corresponds to hydraulic retention time (h or d), the *V* is the volume of the bioreactor (m$^3$), and *Q* is the influent flow rate (m$^3$/d).

*Organic loading rate (OLR)*

OLR has been the main parameter that significantly affects the microbial ecology and functioning of EGSB bioreactor process. This parameter corresponds to the amount of organic matter introduced into the bioreactor per unit of volume and time. Low values imply low concentration in the influent and/or high hydraulic retention time. The increase in the OLR implies a reduction in the production of biogas per unit of organic matter introduced, having to find an optimal technical/economic value for each type of wastewater to be treated. In the case of EGSB bioreactor, the OLR is generally applied in the range of 1.0 up to 40 Kg COD/m$^3$d. However, if the OLR increases above 40 kg COD/m$^3$d, it will cause an operational problem in the EGSB bioreactor, although the biogas production increases to a certain extent, the balance, and performance of the EGSB bioreactor can also be significantly disturbed. Adding a large volume of new wastewater daily can cause changes in the environment of the bioreactor and temporarily inhibits the microbial metabolic activity during the early stages of digestion (Cruz-Salomón, 2018). This microbial metabolic activity inhibition occurs due to an extremely high OLR value that leads to greater hydrolysis/acidogenesis activity than the activity of methanogenesis and, therefore, increases the production of volatile fatty acids (VFA), which ultimately leads to irreversible acidification. After that, the pH of the bioreactor decreases, and the hydrolysis process is inhibited such that restricted methanogenic archaea cannot convert so much VFA into methane. Hence, the bioreactor begins to operate poorly (Rincón *et al.,* 2008; Nagao *et al.,* 2012, Kougias *et al.,* 2013, Gou *et al.,* 2014; Mao *et al.,* 2015). The OLR can be changed by modifying the influent concentration or by the flow rate (Q). Thus, implies modifying the HRT and Q, under these conditions, OLR can be calculated using Eq. 3.

$$\mathrm{OLR} = \frac{\mathrm{Q} * \mathrm{COD}}{\mathrm{V}} = \frac{\mathrm{COD}}{\mathrm{HRT}} \qquad (3)$$

Where OLR corresponds to the organic loading rate (kg COD/m$^3$·d), *Q* is flow rate (m$^3$/d), COD is chemical oxygen demand (kg COD/m$^3$), *V* is the volume of the bioreactor (m$^3$), and HRT is hydraulic retention time (d).

*Upflow velocity ($V_{up}$)*

The upflow velocity has been another factor affecting the efficiency of the bioreactors (GonCalves *et al.,* 1994; Wiegant, 2001; Metacalf *et al.,* 2013). The $V_{up}$ affects the AGS retention since it is based on the sedimentation characteristics of the sludge aggregates. In addition to that, the flow rate could be a limiting factor regarding the bioreactor volume required to treat wastewater with high concentration of organic matter and wastewater with a high content of suspended solids (Wiegant, 2001). The $V_{up}$ has two opposite effects: firstly, by increasing the $V_{up}$, the rate of collision or shock is increased (between particles of influent water and the particles making up the mantle or sludge bed), as well as the area of contact between influent suspended particles and AGS, improving the performance of bioreactor. On the contrary, by increasing the $V_{up}$, it may increase the hydraulic shear rate, which counteracts the removal mechanism for exceeding the sedimentation velocity of most particles and, consequently, worsen the performance of bioreactor. (Mahmoud *et al.,* 2003; Iñiguez-Covarrubias and Camacho-López, 2011). The upflow velocity can be calculated using Eq. 4.

$$V_{up} = \frac{\mathrm{H}}{\mathrm{HRT}} \qquad (4)$$

Where $V_{up}$ corresponds to upflow velocity (m/h), H is the height of bioreactor (m), and HRT is hydraulic retention time (h).

*Particle-size distribution (PSD)*

The particle-size distribution (PSD) of the organic matter or granular material present according to size particles or dispersed in the wastewater may significantly affect the speed, stability, and performance of EGSB bioreactor. Many researchers have reported that the smaller the particle-size in the wastewater, the greater the performance by the EGSB bioreactor (Landa *et al.,* 1997; Abdelgadir *et al.,* 2014; Cruz-Salomón, 2018).

*Hydrodynamics of the EGSB bioreactor*

Hydrodynamics is a very important factor in the study of EGSB bioreactor because it can influence the rates of biological reactions through changes in the rate of mass transfer and the distribution of reactions along the bioreactor. Also, it can determine the existence of short circuits of liquid, preferential roads, poor distribution of influent, stagnant or poorly mixed regions, which have very adverse effects on the functioning of the bioreactor. In the literature, usually, the hydrodynamics of EGSB bioreactors is considered as a complete mix and plug flow (because of recirculation of the liquid that entering through the lower part of the bioreactor). This bioreactor presents a non-homogeneous operation system which means that the treatment is carried out through three phases, 1) solid (AGS), 2) liquid (wastewater), and 3) gas (biogas).

*Fluid dispersion*

The behavior of the fluid in the bioreactor generated by the mixing intensity is determined by the Peclet $_{axial}$ number ($Pe_{axial}$) that is in function of the axial dispersion coefficient ($D_A$), i.e., the degree of back-mixing in the bioreactor (Levenspiel, 2002). $Pe_{axial}$ can be calculated using Eq. 5.

$$\mathrm{Pe}_{\mathrm{axial}} = \frac{V_{up} * \mathrm{H}}{D_A} \quad (5)$$

Where $Pe_{axial}$ corresponds to Peclet $_{axial}$ number, $V_{up}$ is upflow velocity (m/h), H is bioreactor height (m), and $D_A$ is axial dispersion coefficient ($m^2/h$). When $D_A$ is minimal Pe$\rightarrow \infty$, this means piston-type flow, on the other hand when $D_A$ is maximum Pe$\rightarrow$0, so that can be considered as a complete mix (Guo, 2012). The $D_A$ can be calculated using Eq. 6.

$$D_A = 1.03 V_{up}^{1.11} * 0.009^{n_j} \quad (6)$$

$$\mathrm{n_j} = \frac{\mathrm{z}}{\mathrm{H}} \quad (7)$$

Where $D_A$ corresponds to axial dispersion coefficient ($m^2/h$), $V_{up}$ is upflow velocity (m/h), and $n_j$ is the value of the normalized height of the bioreactor ($n_j$ can be calculated using Eq. 7, where z is an axial position (estimation point), and H is bioreactor height (m).

*Bioreactor turbulence*

The turbulence generated in the bioreactor is characterized by the Reynolds number, this number is a conventional parameter and it can be calculated using the Eq. 8.

$$\mathrm{Re} = \frac{V_{up} * d}{v_w} = \frac{\rho_w * V_{up} * d}{\mu_w} \quad (8)$$

Where Re corresponds to Reynolds number (dimensionless), $V_{up}$ is upflow velocity (m/h), *d* is the diameter (m) of the bioreactor in the digestion zone, $v_w$ is kinematic viscosity ($m^2/s$), $\mu_w$ is the dynamic viscosity of the wastewater (Pa·s), and $\rho_w$ is the density of the wastewater ($kg/m^3$). The ranges of operating regimes are (Welty, 2014): laminar - when Re < 2300, transient - when 2300 < Re < 4000 or turbulent - when Re > 4000.

*Settling velocity ($u_t$)*

The settling velocity of AGS determines the robustness of the biomass to support the hydrodynamic stress, shear rate in AGS maintaining its integrity and density to avoid washing. In this way, it has also been considered as an operating parameter to determine granular viability and estimate the operating organic loads. The calculated of settling velocity is based on the Stokes's Law for spherical particles in laminar flow regimes, based on the vertical fall of the particle (AGS) due to its weight, where the friction force is equal to the apparent weight of the particle. Settling velocity can be calculated using Eq. 9 (the current equation is the correction of Stokes Law is through Allen's Law) (Yong-Hong *et al.*, 2006).

$$u_t = 0.781 \left( \frac{d_s^{1.6} * (\rho_g - \rho_w)}{{\rho_w}^{0.4} * {\mu_w}^{0.6}} \right)^{0.714} \quad (9)$$

Where $u_t$ corresponds to the settling velocity (m/h), $d_s$ is the Sauter mean diameter (m) of the floc, $\rho_g$ is the granular density ($kg/m^3$), $\rho_w$ is the density of the wastewater ($kg/m^3$), and $\mu_w$ is the viscosity of the wastewater (Pa·s).

*Bed expansion*

The expansion of the bed plays a key role in the operation, design, and hydrodynamics of an EGSB bioreactor since it is the imminent point to achieve an adequate balance between bed expansion and AGS washout. So that, the stability and performance of the EGSB bioreactor depend on sensitive to the degree of bed expansion (Liu *et al.*, 2002; Liu *et al.*, 2006). Thus, it is recommended to bed expansion up to 60 % of the total height of the bioreactor to avoid AGS washout. The expanded bed height under different operating conditions can be calculated using Eq. 10.

$$H_e = H_o \left( 1 + \frac{\dfrac{\ln \frac{u}{u_t}}{e^{4.4} * Re_t^{-0.1}} - 0.4}{1 - \dfrac{\ln \frac{u}{u_t}}{e^{4.4} * Re_t^{-0.1}}} * 100\% \right) \quad (10)$$

Where $H_e$ corresponds to bed-expansion height (m), $H_o$ is initial bed height (m), $Re_t$ is Reynolds number at terminal velocity, $u$ is settling velocity of collective of particles (m/h), and $u_t$ is mean settling velocity of the granules (m/h).

*Shear rate*

To calculate the shear rate ($\gamma$) Wu *et al.* (2012) found an equation to calculate the shear rate in function of the Reynolds number (around the granule) which can be calculated using Eq. 11. This equation demonstrates that the shear rate exerted on the granules is linearly correlated to the Reynolds number. In such a way that as the liquid velocity and granule size increases, the shear rate also augments.

$$\gamma = 3.52 Re_g + 1.889 \tag{11}$$

$$Re_g = \frac{\rho_w * V_{up} * d_s}{\mu_w} \tag{12}$$

Where $\gamma$ is the average shear rate en (1/s), is Reynolds number in the granule surface ($Re_g$ can be calculated using Eq. 12), $V_{up}$ is upflow velocity (m/h), $d_s$ is the Sauter mean diameter (m) of the granule, $\mu_w$ is the viscosity of the wastewater (Pa·s), $\rho_w$ is the density of the wastewater (kg/m$^3$).

*Mathematical model*

Although EGSB bioreactor has been widely used in the wastewater treatment for more of 30 years, limited publications on mathematical modeling have been reported about this bioreactor. Due to its higher upflow velocities, which are caused by a high recycle rate and the AGS bed expansion through the whole bioreactor have made it difficult to develop precise mathematical modeling. However, based on the knowledge of UASB bioreactors and FBR models, modeling of EGSB bioreactor can be attempted. Usually, the hydrodynamic behavior of an EGSB bioreactor has been considered as a complete mix reactor (Fuentes *et al*., 2011; López and Borzacconi, 2011). Contrarily, Bhattacharyya and Singh (2010) considered that the hydrodynamics of the EGSB bioreactor as a plug flow with recirculation and dead space, with high dispersion. However, studies conducted by Teixeira-Correia *et al.* (2014) showed that the EGSB bioreactor can be modeled with two types of ideal reactors, the plug flow (tubular) and the complete mix. So that the EGSB bioreactor can be divided into two regions (tube and separator). The region of the tube showed the behavior of a tubular reactor with high dispersion, while the region of the separator shows the behavior of a complete mix reactor.

*Model of the tubular reactor with dispersion*

The tubular reactor model is an example of a model with distributed parameters, in which it is assumed that the properties vary along the reactor. Since it is a model where the reaction term will not be taken into consideration, the concentration over time is the addition of the convection and diffusion phenomena. Model equations and boundary conditions are described in Eqs. 13 to 16 (Teixeira-Correia *et al.*, 2014).

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial z^2} - v\frac{\partial C}{\partial z} \tag{13}$$

$$\ln z = 0\,; D\,\frac{\partial C}{\partial z} = v\,(C_1 - C_{in}) \tag{14}$$

$$\ln z = L\,;\ \frac{\partial C}{\partial z} = 0 \tag{15}$$

$$C_{in} = \frac{Q_a C_a + Q_r C_r + Q_i C_i}{Q_a + Q_r + Q_i} \tag{16}$$

In the resolution of the equations of the model, the method of central finite differences of second order was used, of which first and second-order approaches are described in Eqs. 17 and 18, respectively.

$$\frac{\partial C}{\partial z} = \frac{C_{i+1} - C_{i-1}}{2dz} \tag{17}$$

$$\frac{\partial^2 C}{\partial z^2} = \frac{C_{i+1} - 2C_i + C_{i-1}}{dz^2} \tag{18}$$

By substituting Eqs. 17 and 18 in the equation of the tubular reactor with dispersion Eq. 13, there is Eq. 19.

$$\frac{\partial C}{\partial t} = \frac{D}{dz^2}\,(C_{i+1} - 2C_i + C_{i-1}) - \frac{v}{2dz}(C_{i+1} - C_{i-1}) \tag{19}$$

Where z is the axial position coordinate (cm), C is the concentration of substrate in the reactor outlet (mol/cm$^3$), t is the time (sec), v is the mean upflow velocity (cm/sec), Q is the flow rate (m$^3$/sec), D is the mass axial dispersion coefficient (cm$^2$/sec), $C_{in}$ is the inlet concentration (mol/cm$^3$), $Q_a$ is the affluent flow ($m^3$/sec), $C_a$ is the affluent concentration (mol/$cm^3$), $Q_r$ is the recirculation flow ($m^3$/sec), $C_r$ is the concentration of recirculation (mol/$cm^3$), $Q_i$ is the flow rate of the tracer ($m^3$/sec), and $C_i$ is the concentration of the tracer (mol/$cm^3$).

*Continuous stirred-tank reactor (CSTR) Model*

The CSTR model is also known as complete (or perfect) mix model. It is an example of a lumped model, where it is considered that properties, such as concentration, do not vary along with the position coordinates. The modeling is based on mass balance, where the mass that is accumulated in the volume control (V) per time unit is equal to the mass that enters it per time unit minus the mass that leaves it per time unit, as described in Eq. 20.

$$V\frac{dC_i}{dt} = Q_0 C_{i_0} - QC_i \quad (20)$$

According to Teixeira-Correia *et al.* (2014), the best combination for mathematic model EGSB bioreactor was with five CSTRs (three in the region of the tube and two in the region of separator) or with two tubular reactors in series (the first in the region of the tube, and the second in the region of the separator). The presented mathematic models previously described can be used to describe the hydrodynamic behavior of the EGSB bioreactor.

*Earlier Work by Various Investigators*

*Wastewater Treatment using EGSB bioreactor*

Nowadays, EGSB bioreactor technology is used for treatment of various kinds of wastewater from agro-industry and chemical, biochemical, biotechnological industries (i.e., Agro-food, beverage, pharmaceutical, chemical, textile, miscellaneous, among others) around the world (Zhang *et al.,* 2008; Mao *et al.,* 2015; Cruz-Salomón *et al.,* 2017b). Installation of the EGSB bioreactors for industrial wastewater treatment has grown very fast in the last 15-20 years (increasing popularity), as shown in Fig. 5. This high demand and popularity acquired by these bioreactors in the recent years can be attributed to the fact that it is a technology that operates at low-cost, with design simplicity and it does not use sophisticated equipment. In addition to generates high treatment efficiency (similar to aerobic processes) and high yield of renewable energy production. These factors together with the greater experience in the granulation of the AGS and the higher availability of AGS, have led to the success to this bioreactor (van Lier, 2008). Currently, Paques and Biothane are the primary Dutch constructors of this technology, and they sell more EGSB bioreactors than conventional UASB bioreactors (van Lier, 2008; van Lier *et al.,* 2015) so that the EGSB type of bioreactors is becoming more popular. Fig. 6. Shows the number of the commercial scale EGSB bioreactors built in the

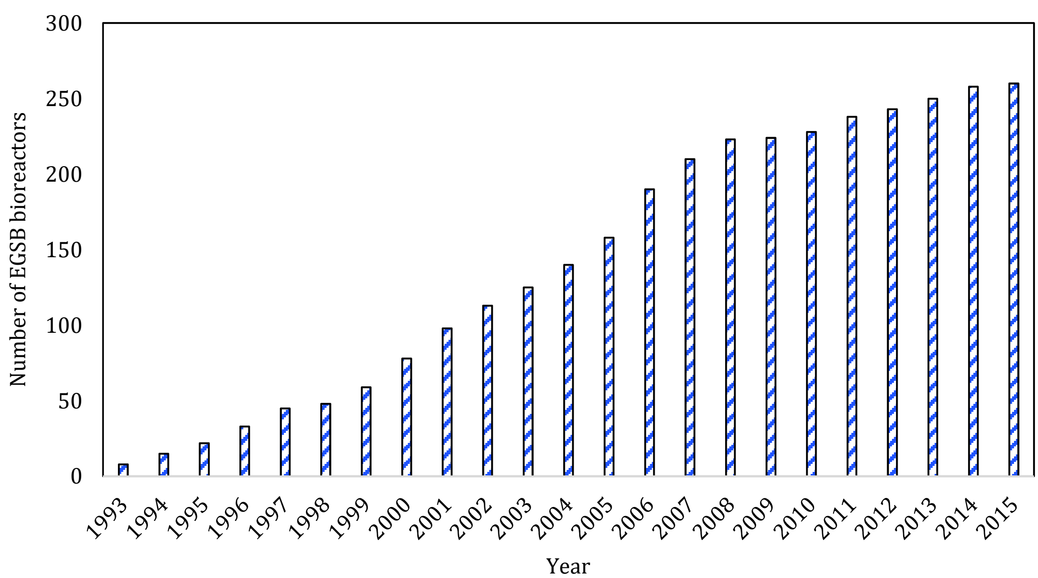


Fig. 5: Relative number of sales of Biobed EGSB bioreactors by Biothane-Veolia, period 1993–2015.

world for treating different wastewaters until 2003 adapted from Kleerebezem and Macarie, (2003).

*Application and Development Trends*

Table 1 presents a detailed review of the EGSB technology used in recent years for the treatment of wastewater and biogas production, in this analysis is described to detail the operating characteristics, design, construction and results obtained by several researchers. In the last decades, as the knowledge in the field of the EGSB bioreactor is progressing, it is gaining greater acceptance unlike the 90's, where it was an almost unknown technology. Due to its popularity, the scientific community has focused on this type of bioreactor to study it. Because of this, several researchers have reported the evaluation of this bioreactor with different types of wastewater where Cruz-Salomón *et al.* (2018) evaluated the treatment of CPWW using a laboratory scale EGSB bioreactor at different HRTs (7 different HRTs). The results evidenced that the EGSB bioreactor showed a good performance in the treatment of CPWW, so it can be a sustainable alternative to treat these types of wastewater compared to traditionally used treatment methods. Cruz-Salomón *et al.* (2017a) and Ramos-Vaquerizo *et al.* (2018) investigated laboratory-scale anaerobic EGSB bioreactors to explore the feasibility of treating three most significant agro-industrial wastewaters in Mexico (cheese whey, vinasse, and CPWW). They deduced that the EGSB bioreactors are a sustainable alternative to simultaneously solve the water pollution crisis and produce bioenergy. Zhang *et al.* (2008), Fang *et al.* (2011a) and Wang *et al.* (2015) evaluated EGSB bioreactors to treat POME. They reported a high COD removal efficiency and concluded that this bioreactor can be a good alternative to treat POME and produce renewable energy. Liu *et al.* (2011) determined that it is possible to treat fresh leachate of municipal solid waste in EGSB bioreactor with efficient energy recovery and high COD removal. However, even though the EGSB bioreactor generates high removal efficiencies in the treatment of agro-industrial and industrial wastewater, like other anaerobic systems, it still cannot produce a final effluent that meets dischargeable standards. Other studies as Li *et al.* (2007), Chen et al. (2008b), Chen et al. (2011), Bai *et al.* (2013), Liao *et al.* (2014), Gao *et al.* (2015) reported the feasibility of treating low-load and high-load real sewage with high levels of sulfate, phosphate or nitrogen in EGSB bioreactors. In these studies, the results showed that this type of technology was found to be very useful for the removal of not only COD but also from sulfate, phosphate, and nitrogen. Instead, Enright *et al.* (2005), Scully *et al.*

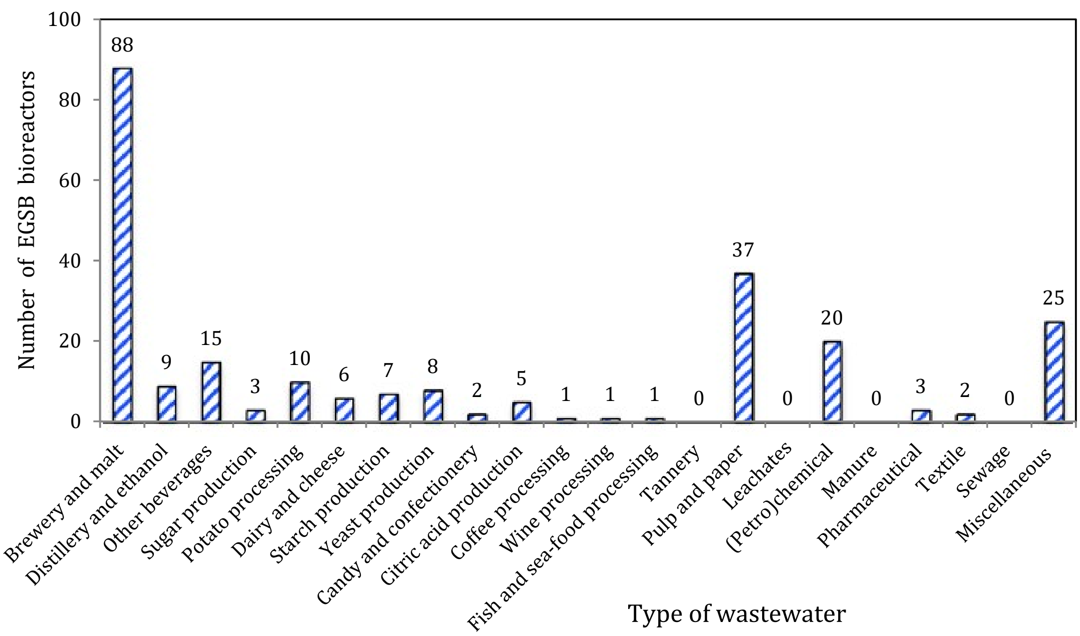


Fig. 6: Number of the commercial scale EGSB bioreactors built in the world for treating wastewaters

Table 1: Treatment performance for wastewater with EGSB technology

| Bioreactor Type | Type of Wastewater | Operating Conditions | | | | | H/Ø | Inoculum | | COD | Efficiency | | References |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Bioreactor Vol. (L) | Temp. (°C) | HRT (h) | $V_{UP}$ (m/h) | OLR (kg COD/m³ d) | | Ø (mm) | Vol. (L) | Influent (mg/L) | COD Removal (%) | Biogas Production (L/day) | |
| EGSB | Vinasse | 12 | 30 | NP | NP | NP | NP | NP | NP | 18,000 – 40,000 | NP | NP | López and Borzacconi, 2011 |
| EGSB | Vinasse | 3.3 | 26 | 168 | NP | 5.1 | 15.8 | 0.5 - 1 | 1 | 9648 | 75 | 4.2** | Ramos-Vaquerizo *et al.*, 2018 |
| EGSB | Vinasse | 12.5 | 35 | 15 | 0.19 | 4.8 | 9.5 | NP | 3 | 6,000 | 73.4 | NP | Qinglin *et al.*, 2012 |
| EGSB | POME | 21.56 | 35 | 48 | 3.5 | 1.45 – 17.5 | 17.72 | NP | 12 | 4,331 - 35,000 | 91 | NP | Zhang *et al.*, 2008 |
| EGSB | POME | 423900 | 35 | 10 | 0.13 | NP | NP | 1 – 3.5 | NP | 71,179 | 82.6 | 1,264,800 | Wang *et al.*, 2015 |
| EGSB | POME | 1.3 | 55 | 240 & 120 | NP | 1.3 – 10.4 | NP | 0.25 – 0.5 | 0.2 | NP | >90 | 0.531 – 3.527 | Fang *et al.*, 2011a |
| EGSB | Fresh Leachate | 6 | 35 - 37 | 17 | 5 | 5.59 – 37.94 | 15 | 1 - 2 | NP | 3,900 – 26,468 | 93 | 1.81 – 12.75 | Liu *et al.*, 2011 |
| EGSB | SW | 20 | 2, 10 & 15 | 3, 4 & 6 | 5 | 3 - 6 | NP | NP | NP | 600 - 800 | NP | NP | Syutsubo *et al.*, 2008 |
| EGSB | SW | 16.8 | 20 | 1.5 | 5 | 12 | 12.7 | 2 | NP | 600 - 800 | 73 – 82 | NP | Yoochatchaval *et al.*, 2008 |
| UAFB-EGSB | SW | 1 | 30, 20 & 10 | 6 | 7 | 1.05, 0.78 & 0.45 | 20 | NP | NP | NP | 84.7 -90-6 | 0.009 – 0.025 | Gao *et al.*, 2015 |
| EGSB-SBR | SW | 2.5 | 30-35 | 40 – 3.3 | NP | 1.62 – 2.77 | 13 | NP | NP | 4,500 - 200 | 88.34 – 98.86 | 0.23 – 1.99 | Bai *et al.*, 2013 |
| EGSB-ZBF | SW | 5.67 | 35 | 0.32 - 6 | 0.51 - 9.69 | 1.66 – 7.55 | 36 | NP | 0.8 | 150 ± 100 | 56 – 82.7 | NP | Li *et al.*, 2007 |
| Anammox-EGSB | SW | 1.2 | 35 | 8 | NP | 0.76 – 22.87• | NP | 2.2 | 0.75 | 112.8 – 767.2• | 90.6 & 99.5⁺ | NP | Chen *et al.*, 2011 |
| EGSB | SW | 1.4 | 30 | 10 - 4 | 3 | 24 - 60 | 22.32 | NP | NP | NP | NP | 4.23* | Cisneros-Pérez *et al.*, 2015 |

Table 1 (*Continued*): Treatment performance for wastewater with EGSB technology

| Bioreactor Type | Type of Wastewater | Operating Conditions | | | | | H/Ø | Inoculum | | COD | Efficiency | | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Bioreactor Vol. (L) | Temp. (°C) | HRT (h) | $V_{UP}$ (m/h) | OLR (kg COD/m$^3$ d) | | Ø (mm) | Vol. (L) | Influent (mg/L) | COD Removal (%) | Biogas Production (L/day) | |
| EGSB | SW | 61 | 37 | 35 - 49 | 0.05 | 1.853 | NP | NP | 40 | 3,000 | 98 | 8.64 – 33.12 | Colussi *et al.*, 2009 |
| EGSB | SW + Brine | 1.96 | 35 | 15 | 2.5 | NP | 170 | > 0.2 | NP | 2,000 – 7,200 | 85 - 94 | NP | Liao *et al.*, 2014 |
| EGSB | SW + MPB | 15 | NP | 25 - 27 | NP | 0.86 - 0.99 | 29.6 | 0.1 – 0.6 | NP | 500 | 95 | NP | Londoño and Peñuela, 2015 |
| EGSB | SW + Pesticides | 5.2 | 35 | 24 | 2.5 | 1.75 | 7.2 | NP | NP | NP | 85 | NP | Monsalvo *et al.*, 2014 |
| EGSB | Phenolic Wastewaters | 3.5 | 9.5 - 15 | 12 - 24 | 5 | 5 - 10 | NP | 0.5 – 1 | 0.75 | 5,000 | 60 - 98 | 2.5 – 3.5 | Scully *et al.*, 2006 |
| EGSB | Pharmaceutical Wastewater | 4 | < 20 | 6, 12 & 24 | 10 | 5, 10 & 20 | NP | NP | NP | 5,000 | 60 - 70 | NP | Enright *et al.*, 2005 |
| EGSB | Oxytetracycline Florfenicol | 15.2 | NP | 0.79<br>0.83 | NP | 0.69 – 1.56<br>0.69 – 1.45 | 29.8 | 2.35 | NP | NP | 86<br>91 | NP | Bhattacharyya and Singh, 2010 |
| EGSB | M2P | 19 | 18 & 25 | NP | 9.2 – 12.8 | 6 – 45 | 18.53 | NP | NP | NP | 95 | NP | Lafita *et al.*, 2015 |
| EGSB | Domestic Wastewater | 4.7 | 11 - 25 | 3.5 – 5.7 | 4 | NP | 30.35 | 0.32 – 2 | NP | 383 - 849 | 85 - 96 | 0.28 – 0.58 | Chu *et al.*, 2015 |
| EGSB | SDIW | 24 | 35 – 37 | 12 | 0.85 | 11 | 19.9 | NP | 9 | 1,167 – 9,950 | 93 | 17 | Sheldon and Erdogan, 2017 |
| EGSB | SBW | 15 | 20 & 15 | 18 | 2 | NP | NP | NP | NP | 7,300 & 4,100 | 85 - 90 | NP | Xing *et al.*, 2009 |
| EGSB | Potato Juice | 1 | 37 | 144 - 240 | NP | 2.5 – 4.2 | 92 | NP | 0.2 | 25,200 | NP | 0.84 – 1.42 | Fang *et al.*, 2011b |

SDIW (Soft drink industry wastewater); SW (Synthetic Wastewater); SBW (Synthetic brewery wastewater); POME (Palm oil mill effluent); MPB (Methylparaben); M2P (1-methoxy-2-propanol); ZBF (Zeolite bed filtration); SBR (Sequencing batch reactor); UAFB (Upflow anaerobic fixed bed bioreactor).
NP: not provided
•Concentration ammonium and nitrite
*$H_2$ production
**$CH_4$ production

(2006), Londoño *et al.* (2012), Monsalvo *et al*. (2014), Londoño and Peñuela (2015), and Lafita *et al*. (2015) analyzed the effect of recalcitrant compounds, such as antibiotics (like oxytetracycline and florfenicol), phenol, methylparaben (MPB), solvent-containing pharmaceutical and pesticides on the operation of EGSB bioreactors. The results showed a high removal efficiency for treat oxytetracycline (OTC), florfenicol (FLO), phenol, MPB, solvent-containing pharmaceutical (like propanol, methanol, ethanol, 1-methoxy-2-propanol (M2P), and acetone) and pesticides (2-methyl-4-chlorophenoxyacetic acid (MCPA), imidacloprid and dimethoate) up to 68 %, 99 %, 70 %, 95 %, 90 % and 85 %, respectively. These studies presented novel results since they allow demonstrating that the technology constituted by EGSB bioreactors is capable of removal of specific contaminants such as antibiotics, pesticides, and amount other recalcitrant compounds. So that, these studies can shift the paradigm of EGSB bioreactor use from only organic matter removal to nutrients and recalcitrant compounds removal. Nevertheless, to achieve higher removal efficiency values of the pollutants present in wastewater, the EGSB bioreactors have been coupled with different systems, e.g., Chu *et al*. (2015) informed that a membrane-coupled EGSB bioreactor could treat domestic wastewater under mesophilic to psychrophilic conditions with had high total organic carbon (COT) and COD removal efficiency. Sheldon and Erdogan (2017) evaluated a multi-stage EGSB coupled aerobic membrane bioreactor (MBR) for the treatment of SDIW. This system (EGSB-MBR) without adding external carbon sources and nutrients generated high organic matter removal efficiency and high yield of biogas production. Li *et al.* (2007) evaluated an EGSB coupled with zeolite bed filtration (ZBF) for treatment of low strength domestic wastewater to remove carbon and nutrient (N and P). They found that the system (EGSB-ZBF) is efficient for COD, $NH_4^+$, and $PO_4^{-3}$ removal. Gao *et al.* (2015) designed and verified a system combined an upflow anaerobic fixed bed (UAFB) and an EGSB bioreactor for treating real domestic wastewater. They conclude that this system (UAFB–EGSB) has high efficiency for treating real domestic wastewater with simultaneous energy recovery and autotrophic nitrogen removal. Moreover, Collins *et al.* (2003 and 2005), Enright *et al.* (2005), Scully *et al.* (2006), Yoochatchaval *et al.* (2008), Xing *et al.* (2009) and Chu *et al.* (2015) conducted investigations with EGSB bioreactors in psychrophilic conditions. They show that the EGSB bioreactor is a feasible system for anaerobic treatment at low temperature, even Syutsubo *et al.* (2008) confirmed that both acetate-fed and hydrogen-fed methanogenic activities was good in psychrophilic conditions and Connaughton *et al.* (2006) demonstrated that there was no difference between the mesophilic EGSB bioreactor and the psychrophilic one. These results present a great advance in the EGSB technology since other anaerobic technologies generate less efficiency in wastewater treatment under psychrophilic conditions. So that, this technology could be used efficiently in wastewater treatment for developing countries with temperate or tropical climates. According to reported by the researchers (Ozgun *et al.,* 2013; Cruz-Salomón *et al.,* 2017a; Cruz-Salomón, 2018) above mentioned that the EGSB bioreactor has excellent performance in the treatment of high-load (i.e., industrial and agro-industrial wastewater) and low-load (i.e., domestic) wastewater, at different operating conditions, which makes it a versatile bioreactor with an attractive alternative to reduce environmental pollution and generate renewable energy (i.e., biogas, biomethane, and biohydrogen).

## CONCLUSION

EGSB bioreactors are feasible to treat different types of wastewaters that come from industrial, agro-industrial and domestic. The performance of these bioreactors gets affected by the substrate, pH, HRT, SRT, OLR, $V_{up}$, PSD, temperature and H/D ratio; however, these bioreactors performance are efficient to remove organic pollutants with high renewable energy production, provided that the aforementioned parameters are in an appropriate condition where there is not accumulation of VFA. The EGSB bioreactor can be a novel sustainable alternative for the efficient treatment of different types of wastewater (domestic, industrial and agro-industrial) as compared to other conventional methods. In addition, this bioreactor can help solve the crisis of water pollution, it can even generate environmental benefit like renewable energy production (biogas, biomethane, and biohydrogen), reduces the emission of greenhouse gases (substituting conventional energy sources by renewable energy), water protection (water pollution reduction, eutrophication and acidification reduction), and organic load reduction (agro-industries, industries and domestic wastewater). Also coupled with the cost involved in construction and maintenance that is low and no costs arise other than desludging costs and the operation of feeding pump, go back to the EGSB bioreactor a useful, low-cost technology to wastewater treatment. So that, the EGSB bioreactors can change the paradigm of wastewater management from 'treatment and disposal' to 'beneficial use' as well as 'profitable service'.

## ACKNOWLEDGMENTS

Authors are grateful to the Institute for Research and Innovation in Renewal Energies of the University of Sciences and Arts of Chiapas, to the University of Guanajuato and National Institute of Technology of Mexico-Campus Tuxtla for your support. Also, thank to Dr. Raúl González-Herrera, for helping in polishing the manuscript text writing.

## CONFLICT OF INTEREST

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

## ABBREVIATIONS

| | |
|---|---|
| *AGS* | Anaerobic granular sludge |
| $BOD_5$ | Biochemical oxygen demand |
| *°C* | Degree Celsius |
| *C* | Concentration of substrate |
| $C_a$ | Affluent concentration |
| $Ca(OH)_2$ | Calcium hydroxide |
| $CH_4$ | Methane |
| $C_i$ | Concentration of the tracer |
| $C_{in}$ | Inlet concentration |
| *COD* | Chemical oxygen demand |
| *CPWW* | Coffee processing wastewater |
| $C_r$ | Concentration of recirculation |
| *CSTR* | Continuous stirred-tank reactor |
| *d* | Diameter |
| *D* | Mass axial dispersion coefficient |
| $D_A$ | Axial dispersion coefficient |
| $d_s$ | Sauter mean diameter |
| *EGSB* | Expanded granular sludge bed bioreactor |
| *FBR* | Fluidized bed bioreactor |
| *FLO* | Florfenicol |
| *FOG* | Fats, oil, and grease |
| *GLS* | Gas-Liquid-Solid |
| *H* | Height |
| $H_2S$ | Hydrogen sulfide |
| $H_e$ | Bed-expansion height |
| $H_o$ | Initial bed height |
| *HRT* | Hydraulic retention time |
| *M2P* | 1-methoxy-2-propanol |
| *MBR* | Membrane bioreactor |
| *MCPA* | 2-methyl-4- chlorophenoxyacetic acid |
| *MPB* | Methylparaben |
| *N* | Nitrogen |
| $Na_2SO_4$ | Sodium sulfate |
| $NaHCO_3$ | Sodium bicarbonate |
| *NaOH* | Sodium hydroxide |
| $n_j$ | Normalized height |
| *OLR* | Organic loading rate |
| *OTC* | Oxytetracycline |
| *P* | Phosphorus |
| $Pe_{axial}$ | Peclet $_{axial}$ number |
| *pH* | Potential of hydrogen |
| *POME* | Palm oil mill effluent |
| *PSD* | Particle size distribution |
| *Q* | Flow rate |
| $Q_a$ | Affluent flow |
| $Q_i$ | Flow rate of the tracer |
| $Q_r$ | Recirculation flow |
| *Re* | Reynolds number |
| *RT* | Retention time |
| *SBR* | Sequencing batch reactor |
| *SBW* | Synthetic brewery wastewater |
| *SDIW* | Soft drink industry wastewater |
| $SO_4^{-2}$ | Sulfate |
| *SRT* | Sludge retention time |

| | |
|---|---|
| *SW* | Synthetic wastewater |
| *t* | Time |
| *Td* | Doubling time |
| *TKN* | Total kjeldahl nitrogen |
| *TOC* | Total organic carbon |
| *TSS* | Total suspended solids |
| $u_t$ | Settling velocity |
| *UAFB* | Upflow anaerobic fixed bed |
| *UASB* | Upflow anaerobic sludge blanket bioreactor |
| *V* | Volume |
| *v* | Mean upflow velocity |
| *VFA* | Volatile fatty acid |
| $V_{up}$ | Upflow velocities |
| *z* | Axial position |
| *ZBF* | Zeolite bed filtration |
| *ν* | Kinematic viscosity |
| *γ* | Shear rate |
| *ρ* | Density of the wastewater |
| μ | Dynamic viscosity |

## REFERENCES


Abdelgadir, A.; Chen, X.; Liu, J.; Xie, X.; Zhang, J.; Zhang, K.; Wang, H.; Liu, N., (2014). Characteristics, process parameters, and inner components of anaerobic bioreactors. BioMed. Res. Int., ID 841573, (**10 pages**).

Ahn, J.H.; Forster, C.F., (2002). Comparison of mesophilic and thermophilic anaerobic upflow filters treating paper-pulp-liquors. Process Biochem., 38(2): 256–261 (**6 pages**).

Alphenaar, A., (1994). Anaerobic granular sludge: characterization, and factors affecting its functioning. PhD. Thesis. Department of Environmental Technology, Agricultural University, Wageningen, The Netherlands.

Angelidaki, I.; Ahring, B.K., (1993). Thermophilic digestion of livestock waste: the effect of ammonia. Appl. Microbiol. Biotechnol., 38: 560–564 (**5 pages**).

Angelidaki, I.; Ellegaard, L.; Ahring, B.K., (1993). A mathematical model for dynamic simulation of anaerobic digestion of complex substrates: focusing on ammonia inhibition. Biotechnol. Bioeng., 42: 159–166 (**8 pages**).

Bai, C.; Zhang, D.; He, Q.; Lu, P.; Ai, H., (2013). An EGSB-SBR based process for coupling methanogenesis and shortcut nitrogen removal. Water Sci. Technol., 68(7): 1633-1640 (**8 pages**).

Bhattacharyya, D.; Singh, K.S. (2010). Understanding the mixing pattern in an anaerobic expanded granular sludge bed reactor: effect of liquid recirculation. J. Environ. Eng., 136: 576-584 (**9 pages**).

Boaventura, R.A.; Rodrigues, A.E., (1988). Consecutive reactions in fluidized bed biological reactors: modelling and experimental study of wastewater denitrification. Chem. Eng. Sci., 43: 2715–2728 (**14 pages**).

Borja, R.; Banks, J.C.; Wang, Z., (1995). Kinetic evaluation of an anaerobic fluidized-bed reactor treating slaughterhouse wastewater. Biores. Tech., 52: 163-167 (**5 pages**).

Buffiere, P.; Steyer, J.P.; Fonade, C.; Moletta, R., (1998). Modeling and experiments on the influence of biofilm size and mass transfer in a fluidized bed reactor for anaerobic digestion. Water Res., 32: 657–668 (**12 pages**).

Chan, Y.J.; Chong, M.F.; Law, C.L.; Hassell, D.G., (2009). A review on anaerobic–aerobic treatment of industrial and municipal wastewater. Chem. Eng. J., 155:1–18 (**18 pages**).

Chen, C.; Ren, N.; Wang, A.; Yu, Z.; Lee, D.J., (2008b). Simultaneous biological removal of sulfur, nitrogen and carbon using EGSB reactor. Appl. Microbiol. Biotechnol., 78: 1057–1063 (**7 pages**).

Chen, T.; Zheng, P.; Shen, L.; Ding, S.; Mahmood, Q., (2011). Kinetic characteristics and microbial community of Anammox-EGSB reactor. J. Hazard. Mater. 190(1-3): 28-35 (**8 pages**).

Chen, Y.; Cheng, J.J.; Creamer, K.S., (2008a). Inhibition of anaerobic digestion process: a review. Bioresour. Technol., 99 (10): 4044–4064 (**21 pages**).

Chu, L.B.; Yang, F.L.; Zhang, X.W., (2005). Anaerobic treatment of domestic wastewater in a membrane-coupled expended granular sludge bed (EGSB) reactor under moderate to low temperature. Process Biochem., 40: 1063–1070 (**8 pages**).

Cisneros-Pérez, C.; Carrillo-Reyes, J.; Celis, L.B.; Alatriste-Mondragón, F.; Etchebehere, C.; Razo-Flores, E., (2015). Inoculum pretreatment promotes differences in hydrogen production performance in EGSB reactors. Int. J. Hydrogen Energy., 40(19): 6329-6339 (**11 pages**).

Collins, G.; Foy, C.; McHugh, S.; Mahony, Y.; O'Flaherty, V., (2005). Anaerobic biological treatment of phenolic wastewater at 15 ~ 18°C. Water Res. 39(8): 1614-1620 (**7 pages**).

Colllins, G.; Woods, A.; McHugh, S.; Carton, M.W.; O'Flaherty, V., (2003). Microbial community structure and methanogenic activity during start-up psychrophilic anaerobic digesters treating synthetic industrial wastewaters. FEMS Microbiol. Ecol., 46(2): 159-170 (**12 pages**).

Colussi, I.; Cortesi, A.; Della-Vedova, L.: Gallo, V.; Cano-Robles, F.K., (2009). Start-up procedures and analysis of heavy metals inhibition on methanogenic activity in EGSB reactor. Bioresour. Technol., 100: 6290–6294 (**5 pages**).

Connaughton, S.; Collins, G.; O'Flaherty, V., (2006). Psychrophilic and mesophilic anaerobic digestion of brewery effluent: a comparative study. Water Res., 40(13): 2503-2510 (**8 pages**).

Cruz-Salomón, A.; Ríos-Valdovinos, E.; Pola-Albores, F.; Meza-Gordillo, R.; Lagunas-Rivera, S.; Ruíz-Valdiviezo, V.M., (2017a). Anaerobic treatment of agro-industrial wastewater for COD removal in expanded granular sludge bed bioreactor. Biofuel Res., J. 16: 715-720 (**6 pages**).

Cruz-Salomón, A.; Meza-Gordillo, R.; Rosales-Quintero, A.; Ventura-Canseco, C.; Lagunas-Rivera, S.; Carrasco-Cervantes, J., (2017b). Biogas production from a native beverage vinasse using a modified UASB bioreactor. Fuel., 198: 170-174 (**5 pages**).

Cruz-Salomón, A., (2018). Design and evaluation of EGSB bioreactors for the treatment of agro-industrial wastewaters of the state of Chiapas. Doctoral Thesis. UNICACH. Chiapas, Mexico.

Cruz-Salomón, A.; Ríos-Valdovinos, E.; Pola-Albores, F.;

Lagunas-Rivera, S.; Meza-Gordillo, R.; Ruíz-Valdiviezo, V.M., (2018). Evaluation of hydraulic retention time on treatment of coffee processing wastewater (CPWW) in EGSB bioreactor. Sustainability., 10(1): 83 (**11 pages**).

de la Rubia, M.A., Perez, M., Romero, L.I.; Sales, D., (2006). Effect of solids retention time (SRT) on pilot scale anaerobic thermophilic sludge digestion. Process biochem., 41(1): 79-86 (**8 pages**).

de Man, A.W. A.; Grin, P.C.; Roersma, R.E.; GroUe, K. C. F.; Lettinga, G., (1986). Anaerobic treatment of municipal wastewater at low temperatures. Anaerobic treatment. A grown-up technology. Conference papers (Aquatech '86), Amsterdam., 451-466 (**17 pages**).

Di Felice, R., (1995). Hydrodynamics of liquid fluidisation. Chem. Eng. Sci. 50: 1213–1245 (**33 pages**).

Donoso-Bravo, A.; Retamal, C.; Carballa, M.; Ruiz-Filippi, G.; Chamy, R., (2009). Influence of temperature on the hydrolysis, acidogenesis and methanogenesis in mesophilic anaerobic digestion: parameter identification and modeling application. Water Sci. Technol., 60(1): 9-17 (**9 pages**).

Ekama, G.A.; Wentzel, M.C., (2008). Organic material removal. Biological wastewater treatment: Princ, Modell Des. 53 (**29 pages**).

Enright, A.M.; McHugh, S.; Collins, G.; O'Flaherty, V., (2005). Low-temperature anaerobic biological treatment of solvent-containing pharmaceutical wastewater. Water Res., 39(19): 4587-4596 (**10 pages**).

Fang,C.; O-Thong, S.; Boe K.; Angelidaki, I., (2011a). Comparison of UASB and EGSB reactors performance, for treatment of raw and deoiled palm oil mill effluent (POME). J. Hazard. Mater., 189(1-2): 229-234 (**6 pages**).

Fang, C.; Boe, K.; Angelidaki, I., (2011b). Biogas production from potato-juice, a by-product from potato-starch processing, in upflow anaerobic sludge blanket (UASB) and expanded granular sludge bed (EGSB) reactors. Bioresour. Technol., 102: 5734–5741 (**8 pages**).

Frankin, R.; Koevoets, W.A.A.; van Gils, W.M.A.; van der Pas, A., (1992). Application of the biobed upflow fluidized- bed process for anaerobic wastewater treatment. Water Sci. Technol., 25: 373–382 (**10 pages**).

Frijters, C.T.M.J.; Vos, R.H.; Scheffer, G.; Mulder, R., (2006). Decolorizing and detoxifying textile wastewater, containing both soluble and insoluble dyes, in a full scale combined anaerobic/aerobic system. Water Res., 40(6): 1249–1257 (**9 pages**).

Fuentes, M. A.; Scenna, N.J.; Aguirre, P.A., (2011). A coupling model for EGSB bioreactors: hydrodynamics and anaerobic digestion processes. Chem. Eng. Process. 50 (3): 316-324 (**9 pages**).

Gao, D.W.; Huang, X.L; Tao, Y.; Cong, Y.; Wang, X.L., (2015)., Sewage treatment by an UAFB–EGSB biosystem with energy recovery and autotrophic nitrogen removal under different temperatures. Bioresour. Technol., 181: 26–31 (**6 pages**).

GonCalves, R.F.; Cha-Lier, A.C.; Sammut, F., (1994). Primary fermentation of soluble and particulate organic matter for wastewater treatment. Water Sci. Technol., (30) 6: 53-62 (**10 pages**).

Gou, C.; Yang, Z.; Huang, J.; Wang, H.; Xu, H.; Wang, L., (2014). Effects of temperature and organic loading rate on the performance and microbial community of anaerobic co-digestion of waste activated sludge and food waste. Chemosphere. 105: 146–151 (**6 pages**).

Guo, G., (2012). The effects of local hydrodynamics on mass transfer in disordered porous media. Louisiana State University, Doctoral Dissertations.

Haandel, A.V.; Lubbe, J.V.D., (2007). Handbook biological waste water treatment: design and optimization of activated sludge systems, Anaerobic–aerobic Wastewater Treatment.

Halalsheh, M.; Koppes, J.; Den Elzen, J.; Zeeman, G.; Fayyad, M.; Lettinga, G., (2005). Effect of SRT and temperature on biological conversions and the related scum-forming potential. Water Res., 39(12): 2475–2482 (**8 pages**).

Hermanovicz, S.W.; Ganczarczyk, J.J., (1983). Some fluidization characteristics of biological beds. Biotechnol. Bioeng., 25: 1321–1330 (**10 pages**).

Hulshoff Pol, L.W.; de Castro-Lopes, S.I.; Lettinga, G.; Lens, P.N.L., (2004). Anaerobic sludge granulation. Water Res., 38(6): 1376–1389 (**14 pages**).

Iñiguez-Covarrubias, G.; Camacho-López, A., (2011). Evaluation of an upflow anaerobic sludge blanket reactor (UASB) with changes in the upflow velocity, Ing. Inv. y Tecnol**.**, 12 (1): 199-208 (**10 pages**).

Kato, M. T.; Florencio, L; Arantes, R.F.M., (2003). Post-treatment of UASB effluent in an expanded granular sludge bed reactor type using flocculent sludge. Water Sci. Technol., 48(6): 279-284 (**6 pages**).

Kaviyarasan, K., (2014). Application of UASB Reactor in Industrial wastewater treatment – A Review. Int. J. Sci. Eng. Res., 5: 584-589 (**6 pages**).

Kettunen, R.H.; Rintala, J.A., (1997). The effect of low temperature (5–29 ºC) and adaptation on the methanogenic activity of biomass. Appl. Microbiol. Biotechnol., 48(4): 570–576 (**7 pages**).

Kim, M.; Ahn, Y.H.; Speece, R.E., (2002). Comparative process stability and efficiency of anaerobic digestion; mesophilic vs. thermophilic. Water Res., 36: 4369–4385 (**17 pages**).

Kleerebezem, R.; Macarie H., (2003). Treating industrial wastewater: anaerobic digestion comes of age. Chem. Eng., 56-64 (**9 pages**).

Kougias, P.G.; Boe, K.; Angelidaki, I., (2013). Effect of organic loading rate and feedstock composition on foaming in manure-based biogas reactors. Bioresour. Technol., 144: 1–7 (**7 pages**).

Lafita, C.; Penya-Roja, J. M.; Gabaldón, C., (2015). Anaerobic removal of 1-methoxy-2-propanol under ambient temperature in an EGSB reactor. Bioprocess Biosyst. Eng., 38: 2137–2146 (**10 pages**).

Landa, H.; Capella, A.; Jiménez, B., (1997). Particle size distribution in an effluent from an advanced primary treatment and its removal during filtration. Water Sci. Technol., 36 (4): 159–165 (**7 pages**).

Levenspiel, O., (2002). Ingeniería de las Reacciones Químicas. 2da Edición. Editorial Reverté. Mexico.

Li, X.M.; Guo, L.; Yang, O.; Ming, Z.G.; Xiang, L.D., (2007). Removal of carbon and nutrients from low strength domestic wastewater by expanded granular sludge bed-zeolite bed filtration (EGSB-ZBF) integrated treatment concept. Process Biochem., 42: 1173–1179 (**7 pages**).

Liao, R.; Li Y.; Yu X.; Shi P.; Wang Z.; Shen K.; Shi O.; Miao Y.; Li W.; Li A., (2014). Performance and microbial diversity of an expanded granular sludge bed reactor for high sulfate and nitrate waste brine treatment. J. Environ. Sci., 26: 717–725 (**9 pages**).

Lillo-Cámpora, O.I., (2017). Start-up and operation of an EGSB reactor through simultaneous autotrophic-heterotrophic denitrification for nitrogen, sulfur and organic matter removal. Thesis. Federico Santa María Technical University. Chile.

Liu, Y.H; Xu, H.L.; Show, K.Y.; Tay, J.H., (2002). Anaerobic granulation technology for wastewater treatment. World J. Microbiol. Biotechnol. 18: 99-113 (**15 pages**).

Liu, Y.H.; He, Y.L.; Yang, S.C.; An, C.J., (2006). Studies on the expansion characteristics of the granular bed present in EGSB bioreactors. Water SA., 32(4): 555–560 (**06 pages**).

Liu, J.Y.; Bian, H, D.; Cao, Y.L.; Zhong J.P.; Hu, J.; Liu, Q.; Qian G.R.; Liu F.; Tai J., (2011). Quick start-up of EGSB reactor treating fresh leachate of municipal solid waste. J. Shanghai University., 15(3): 212–217 (**6 pages)**.

Londoño, Y.A.; Peñuela, G.A., (2015). Anaerobic biological treatment of methyl paraben in an expanded granular sludge bed (EGSB). Water Sci. Technol., 71 (11): 1604 – 1610 (**7 pages**).

Londoño, Y.A.; Rodríguez D.C.; Peñuela, G., (2012). The operation of two EGSB reactors under the application of different loads of oxytetracycline and florfenicol. Water Sci. Technol., 66 (12): 2578-2585 (**8 pages**).

López, I.; Borzacconi, L., (2011). Modelling of an EGSB treating sugarcane vinasse using first-order variable kinetics. Water Sci. Technol., 64: 2080-2088 (**9 pages**).

Mahmoud, N.; Zeeman, G.; Gijzen, H.; Lettinga, G., (2003). Solids removal in upflow anaerobic reactors, a review. Bioresour Technol., 90: 1-19 (**19 pages**).

Mao, C.; Feng, Y.; Wang, X.; Ren, X., (2015). Review on research achievements of biogas from anaerobic digestion. Renewable Sustainable Energy Rev., 45: 540–555 (**16 pages**).

Metcalf, E., (2013). Wastewater Engineering-Treatment, Disposal, Reuse. Third edition. New York, USA. McGraw Hill.

Monsalvo, V.M.; Garcia-Mancha, N.; Puyol, D.; Mohedano, A. F.; Rodriguez, J.J., (2014). Anaerobic biodegradability of mixtures of pesticides in an expanded granular sludge bed reactor. Water Sci. Technol., 69(3): 532 – 538 (**7 pages**).

Nagao, N.; Tajima, N.; Kawai, M.; Niwa, C.; Kurosawa, N.; Matsuyama, T., (2012). Maximum organic loading rate for the single-stage wet anaerobic digestion of food waste. Bioresour Technol., 118: 210–218 (**9 pages**).

Nicolella, C.; van Loosdrecht, M.C.M.; Heijnen, J.J., (2000). Wastewater treatment with particulate biofilm reactors. J. Biotechnol., 80: 1–33 (**33 pages**).

Ozgun, H.; Dereli, R.K.; Ersahin, M.E.; Kinaci, C.; Spanjers, H.; van Lier J.B. (2013). A review of anaerobic membrane bioreactors for municipal wastewater treatment: Integration options, limitations and expectation. Sep. Purif. Technol., 118: 89–104 (**16 pages**).

Qinglin, X.; Yanhong, L.; Shaoyuan B.; Hongda J., (2012). Effects of ORP, recycling rate, and HRT on simultaneous sulfate reduction and sulfur production in expanded granular sludge bed (EGSB) reactors under micro-aerobic conditions for treating molasses distillery wastewater. Water Sci. Technol., 66 (6): 1253-1262 (**10 pages**).

Ramos-Vaquerizo, F.; Cruz-Salomón, A.; Ríos-Valdovinos, E.; Pola-Albores, F.; Lagunas-Rivera, S.; Ruíz-Valdiviezo, V.M.; Simuta-Champo, R.; Moreira-Acosta, J., (2018). Anaerobic treatment of vinasse from sugarcane ethanol production in expanded granular sludge bed bioreactor. J. Chem. Eng. Process. Technol., 9(1): 375 (**8 pages**).

Rebac, S.; van Lier, J.B.; Lens, P.; van Cappellen, J.; Vermeulen, M.; Stams, A.J.M.; Swinkels, K.Th. M.; Lettinga, G., (1998). Psychrophilic (6-15 °C) high rate anaerobic traetment of malting wastewater in a two-module expanded granular sludge bed system. Biotech. Progress., 14: 856-864 (**9 pages**).

Rincón, B.; Borja, R.; González, J.M.; Portillo, M.C.; Sáiz-Jiménez, C., (2008). Influence of organic loading rate and hydraulic retention time on the performance, stability and microbial communities of one-stage anaerobic digestion of two-phase olive mill solid residue. Biochem Eng. J., 40: 253–261 (**9 pages**).

Rinzema, A.; Alphenaar, P.A.; Lettinga, G., (1993). Anaerobic digestion of long chain fatty acids in UASB-reactors and expanded granular sludge bed reactors. Process Biochem., 28: 527-537 (**11 pages**).

Sanchez, E.; Borja, R.; Weiland, P.; Travieso, L.; Martin, A., (2001). Effect of substrate concentration and temperature on the anaerobic digestion of piggery waste in a tropical climate. Process Biochem., 37(5): 483–489 (**7 pages**).

Schreyer, H.B.; Coughlin, R.W., (1999). Effects of stratification in a fluidized bed bioreactor during treatment of metal working wastewater. Biotechnol. Bioeng., 63: 129–140 (**12 pages)**.

Scully, C.; Collins, G.; O'Flaherty, V., (2006). Anaerobic biological treatment of phenol at 9.5–15 ºC in an expanded granular sludge bed (EGSB)-based bioreactor. Water Res., 40: 3737–3744 (**8 pages**).

Seghezzo, L., (2004). Anaerobic treatment of domestic wastewater in subtropical regions. Ph.D. thesis, Wageningen University, Wageningen, the Netherlands.

Seghezzo, L.; Zeeman, G.; van Lier, J.B.; Hamelers, H.V.M.; Lettinga, G., (1998). A review: The anaerobic treatment of sewage in UASB and EGSB reactors. Bioresour. Technol., 65: 175–190 (**16 pages**).

Sheldon, M.S.; Erdogan, I.G., (2016). Multi-stage EGSB/MBR treatment of soft drink industry wastewater. Chem. Eng. J., 285: 368–377 (**10 pages**).

Syutsubo, K.; Yoochatchaval, W.; Yoshida, H.; Nishiyama, K.; Okawara, M.; Sumino, H.; Araki, N.; Harada, H.; Ohashi, A., (2008). Changes of microbial characteristics of retained sludge during low-temperature operation of an EGSB reactor for low-strength wastewater treatment. Water Sci. Technol., 57 (2): 277-281 (**5 pages**).

Teixeira-Correia, G.; Pérez-Pérez, T.; Pereda-Reyes, I.; Oliva-Merencio, D.; Zaiat, M.; Hong-Kwong, W., (2014). Mathematical Modeling of the Hydrodynamics of an EGSB Reactor. J. Chem. Chem. Eng., 8: 602-610 (**9 pages**).

van der Last, A.R.M.; Lettinga, G., (1992). Anaerobic treatment of domestic sewage under moderate climatic (Dutch) conditions using upflow reactors at increased superficial velocities. Water Sci. Technol., 25(7): 167-178 (**12 pages**).

van Lier, J.B.; van der Zee, F.; Tan, F.P.; Rebac, S.; Kleerebezem, R., (2001). Advances in high-rate anaerobic treatment: staging of reactor systems. Water Sci. Technol., 44(8): 15–25 (**11 pages**).

van Lier, J.B.; van der Zee, F.P.; Frijters, C.T.M.J.; Ersahin, M.E., (2015). Celebrating 40 years anaerobic sludge bed reactors for industrial wastewater treatment. Rev. Environ. Sci. Biotechnol., 14: 681–702 (**22 pages**).

van Lier, J.B., (2008). High-rate anaerobic wastewater treatment: diversifying from end-of-the-pipe treatment to resource-oriented conversion techniques. Water Sci. Technol., 57(8): 1137-1148 (**12 pages**).

von Sperling, M.; de Lemos-Chernicharo, C.A., (2005). Biological

wastewater treatment in warm climate regions. IWA Publishing.
Wang, J.; Mahmood, O.; Ping Qiu, J.; Sheng Li, Y.; Chang, Y.; Dong Li, X., (2015). Anaerobic Treatment of Palm Oil Mill Effluent in Pilot-Scale Anaerobic EGSB Reactor. Biomed Res. Int., 2015: 1-7 (**7 pages**).
Welty, J.R., (2014). Fundamentals of momentum, heat, and mass transfer. 5th edition. ed. Wiley, Danver, MA. 2008.
Wiegant, W.M., (2001). Experiences and potential of anaerobic wastewater treatment in tropical regions. Water Sci. Technol., (44) 8: 107-113 (**7 pages**).
Wu J.; Bi L.; Zhang, J.B. Poncin, S.; Cao, Z.P.; Li, H.Z., (2012). Effects of increase modes of shear force on granule disruption in upflow anaerobic reactors. Water Res., 46: 3189–3196 (**8 pages**).
Xing, W.; Zuo, J. E.; Dai, N.; Cheng, J.; Li, J., (2009). Reactor performance and microbial community of an EGSB reactor operated at 20 and 15 °C. J. Appl. Microbiol., 107: 848–857 **(10 pages).**
Yong-Hong, L.; Yan-Ling, H.; Shu-Cheng, Y.; Chun-Jiang, A., (2006). Studies on the expansion characteristics of the granular bed present in EGSB bioreactors. Water SA., 32 (4): 555-560 (**6 pages**).
Yoochatchaval, W.; Ohashi, A.; Harada, H.; Yamaguchi, T.; Syutsubo, K., (2008). Characteristics of granular sludge in an EGSB reactor for treating low strength wastewater. Int. J. Environ. Res., 2(4): 319-328 (**10 pages**).
Zhang, L.Y; Yan, L.C.; Long, Z.X.; Mei, Z.Z., (2008). Startup and operation of anaerobic EGSB reactor treating palm oil mill effluent. J. Environ. Sci., 20: 658–663 (**6 pages**).
Zoutberg, G.R.; de Been, P., (1997). The Biobed EGSB (expanded granular sludge bed) system covers shortcomings of the upflow anaerobic sludge blanket reactor in the chemical industry. Water Sci. Technol., 35: 183–188 (**6 pages**).
Zoutberg, G.R.; Frankin, R., (1996). Anaerobic treatment of chemical and brewery wastewater with a new type of anaerobic reactor: the Biobed EGSB reactor. Water Sci. Technol., 34: 375–381 (**7 pages**).

**AUTHOR (S) BIOSKETCHES**

**A. Cruz-Salomón,** Ph.D., Professor, Instituto de Investigación e Innovación en Energías Renovables, Universidad de Ciencias y Artes de Chiapas, Tuxtla Gutiérrez, Chiapas, as well as Departamento de Ingeniería Química y Bioquímica, Tecnológico Nacional de México/ Instituto Tecnológico de Tuxtla Gutiérrez, Tuxtla Gutiérrez, Chiapas, México.
Email: *dr.abumale@gmail.com*

**E. Ríos-Valdovinos,** Ph.D., Professor, Instituto de Investigación e Innovación en Energías Renovables, Universidad de Ciencias y Artes de Chiapas, Tuxtla Gutiérrez, Chiapas, México. Email: *edna.rios@unicach.mx*

**F. Pola-Albores,** Ph.D., Professor, Instituto de Investigación e Innovación en Energías Renovables, Universidad de Ciencias y Artes de Chiapas, Tuxtla Gutiérrez, Chiapas, México. Email: *francisco.pola@unicach.mx*

**S. Lagunas-Rivera,** Ph.D., Professor, Conacyt, Departamento de Química, Universidad de Guanajuato, Guanajuato, Guanajuato, México. Email: *lagunasrs@gmail.com*

**R. Meza-Gordillo,** Ph.D., Professor, Departamento de Ingeniería Química y Bioquímica, Tecnológico Nacional de México/Instituto Tecnológico de Tuxtla Gutiérrez, Tuxtla Gutiérrez, Chiapas, México. Email: *romego71@yahoo.com.mx*

**V.M. Ruíz-Valdiviezo,** Ph.D., Professor, Departamento de Ingeniería Química y Bioquímica, Tecnológico Nacional de México/Instituto Tecnológico de Tuxtla Gutiérrez, Tuxtla Gutiérrez, Chiapas, México. Email: *bioqvic@hotmail.com*

**K.C. Cruz-Salomón,** M.Sc. student, Assistant Professor, Departamento de Ingeniería Química y Bioquímica, Tecnológico Nacional de México/Instituto Tecnológico de Tuxtla Gutiérrez, Tuxtla Gutiérrez, Chiapas, México.
Email: *i.bq.kelly@gmail.com*



**HOW TO CITE THIS ARTICLE**

*Cruz-Salomón, A.; Ríos-Valdovinos, E.; Pola-Albores, F.; Lagunas-Rivera, S.; Meza-Gordillo, R.; Ruíz-Valdiviezo, V.M.; Cruz-Salomón, K.C., (2019). Expanded granular sludge bed bioreactor in wastewater treatment. Global J. Environ. Sci. Manage., 5(1): 119-138.*

**DOI:** 10.22034/gjesm.2019.01.10

**url:** https://www.gjesm.net/article_33289.html