COMPARATIVE ENVIRONMENTAL EXERGY EVALUATION OF WASTEWATER TREATMENT PROCESSES

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Abstract. *This paper presents the exergy analysis of two wastewater treatment systems: an upflow anaerobic sludge blanket reactor located in the rural area of Ginebra (Colombia) and the Wastewater Treatment Plant Barueri located in the Metropolitan Area of São Paulo. The upflow anaerobic sludge blanket (UASB) reactor is an anaerobic treatment system wherein the organic matter is digested, absorbed and metabolized into bacterial cell mass and biogas. Anaerobic digestion is the degradation of organic material without the aid of oxygen. The exergy efficiency of the UASB reactor was calculated as the exergy ratio of the useful effect of the UASB reactor to the total exergy consumed by human and natural resources, including all the exergy inputs. The results are compared with the exergy efficiency of the Wastewater Treatment Plant Barueri. This plant is a conventional and secondary activated sludge treatment and belongs to Tietê River Pollution Reduction Program.The analysis of the results shows that this method can be used to quantify and optimize the environmental performance of wastewater treatment systems.*

Keywords*: exergy efficiency, upflow anaerobic sludge blanket reactor, wastewater treatment systems*

1. INTRODUCTION

The disposal of raw sewage into the environment is one of the most serious and old problems the world. According to the United Nations, less than 20% of the sewage of Latin America and Caribbean receive appropriate treatment Tsukamoto (2002).

There is an increasing demand for more sustainable wastewater treatment systems. However, the criteria needed to characterize such a system are not fully developed. One important tool in the analysis of the sustainability of a wastewater treatment system is the exergy analysis. Hellström (1997) showed how an exergy analysis could be used to estimate the consumption of physical resources in a wastewater treatment plant.

Some authors have suggested that the quantification of the environmental impact of energy conversion processes can be better driven by the use of the exergy concept (Rosen and Dincer, 1997; Gong, 1999; Wall and Gong, 2001). Others went beyond and calculated that impact based on the exergy (Creyts and Carey, 1997; Gong and Wall, 2000; Makarytchev, 1997; Rosen and Dincer, 1999, Lattouf and Oliveira, 2003). The concept of exergy has been used in environmental and ecological fields (Jorgensen, 1988; Jorgensen, 1992a,b), as an ecological indicator and goal function in the ecological modeling for aquatic systems (Bendoricchio and Jorgensen, 1997; Jorgensen and Nielsen, 2007). In addition, it has been used for water quality evaluation, illustrating the relation between exergy and the water quality parameters as COD (Chemical Oxygen Demand), BOD (Biochemical Oxygen Demand), TOC (Total Organic Carbon) (Tai *et al.*, 1986; Chen and JI, 2007; Huang *et al.*, 2007; Chen *et al*, 2007**;** Zaleta-Aguilar *et al*, 1998**;** Gallegos-Muñoz *et al*, 2003**;** Valero *et al*, 2006**;** Hellström, 2003). However, there are not reports about environmental impact evaluation by exergy analysis of the UASB Reactor. According to Szargut *et al.*, 1988, exergy is the amount of work obtainable when some matter is brought to a state of thermodynamic equilibrium with the common components of the natural surroundings by means of reversible processes, involving interaction only with those components of nature.

In this work, the exergy efficiency is used to evaluate and compare the environmental performance of an UASB reactor, located in the rural area of Ginebra (Colombia) with the Wastewater Treatment Plant Barueri located in the Metropolitan Area of São Paulo (Brazil).

2. WASTEWATER TREATMENT PROCESSES

The analysed Wastewater Treatment Processes (WTP), are the WTP Barueri (Fig. 1), that belongs to Tietê River Depollution Program, and the UASB Reactor (Fig. 2) belongs to Research Centre for Sewage Treatment (Ginebra, Colombia).

Figure 1 illustrates a conventional plant of a secondary activated sludge treatment with organic material removal of 90% BOD. The treatment process that takes place in the plant consists of the following stages: a) The Preliminary Treatment consists of two phases: screening and sand removal. Screening removes large solids, which are retained by the screens. The main reasons for the screening are to protect the pumps and tubes, later treatment units and the tanks. The sand is removed by sedimentation.

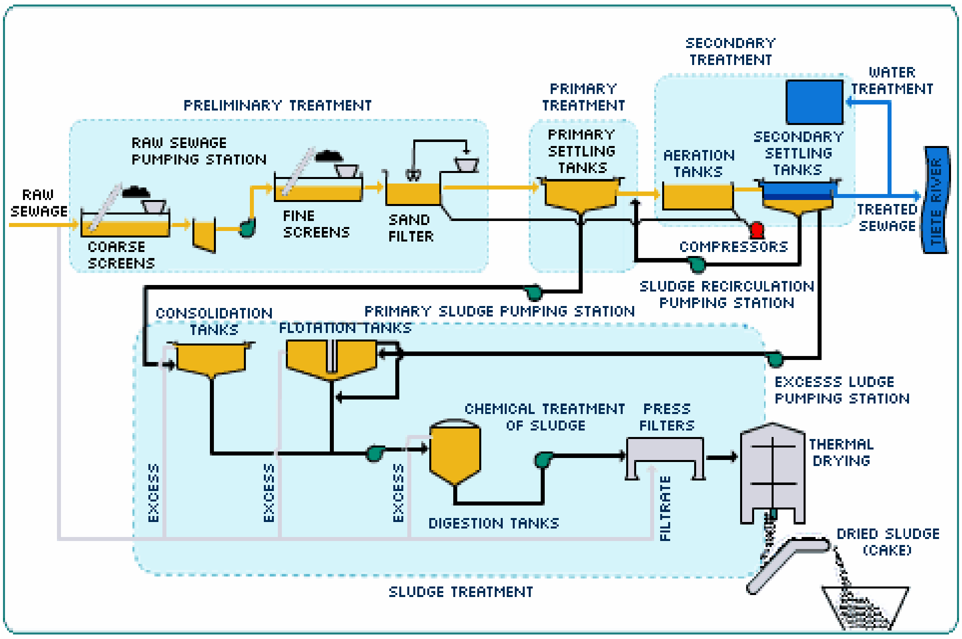

Figure 1. Barueri Wastewater Treatment Plant (SABESP, 2004)

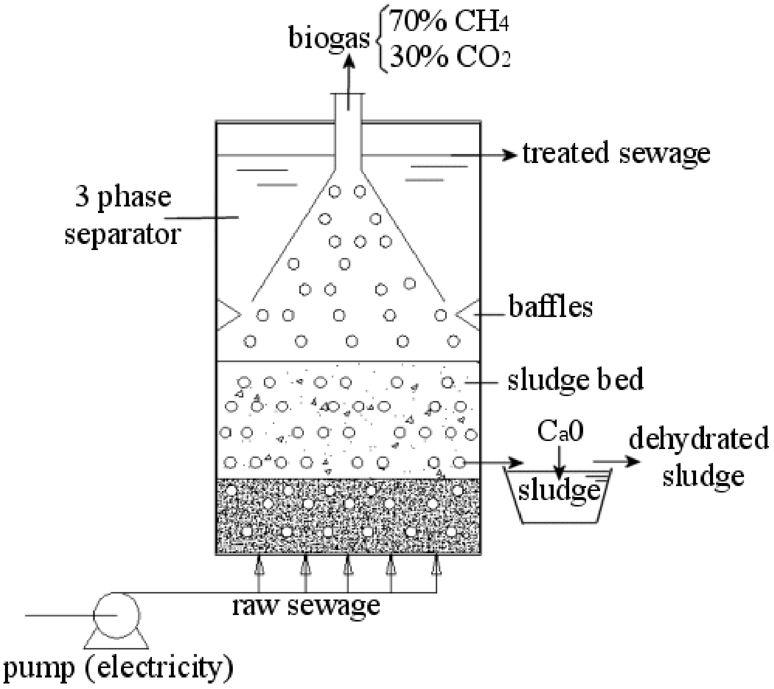

Figure 2. UASB Reactor

The aims of sand removal are to protect the equipment from wear and turbulence, eliminate or reduce the risk of blockages in pipes, tanks, siphons and passages, and simplify the liquid transportation, especially transfer of sludge (see Fig.1).

b) The Primary Treatment consists of primary settling tank which tanks are rectangular or round. Sewage flows slowly through the tanks, allowing suspended solids to gradually settle to the bottom of the tank. This solid mass, called primary sludge, can be consolidated at the bottom of the tank and sent directly for digestion, or can be sent to the consolidation tanks. A large part of these solids is made up of organic matter. Depending on the nature and size of the suspended solids, rotating sieves may be used instead of the screening system or the primary settling tanks. The aim is to separate the larger suspended solids, by means of flowing them through the moving sieves, from the center to the outside. The retained solids are continuously removed in buckets.

c) The Secondary Treatment is made of three phases. In the aeration tank (phase one), organic matter is removed by biochemical reaction, using microorganisms (bacteria, protozoan, fungi) in the aeration tank. This process relies on contact between the microorganisms and the organic material in the sewage, which forms their food. They convert the organic material into carbon dioxide, water and their own cell structure. The secondary settling tanks perform an important function in the activated sludge process (phase two), being responsible for the separation of the suspended solids present in the aeration tank, allowing a clarified liquid to flow out, leaving sediments solids at the base of the tank, which can be returned in a higher concentration. The effluent from the aeration tanks is settled, so that the activated sludge is separated and returns to the aeration tanks. The return of this sludge is necessary to supply the aeration tanks with a sufficient quantity of microorganisms to keep the feeding process going in sufficient strength to decompose the organic material efficiently. The liquid effluent from the secondary settling tanks is either released directly or conveyed for treatment so that it can be reused internally or sold for uses such as washing streets and watering gardens. In the pumping station the excess sludge is sent to the third stage of the secondary treatment: the sludge formed from the suspended solids by means of the alimentation of microorganisms must be removed to maintain equilibrium in the system (solids in = solids out). The sludge is extracted and sent for treatment (see Fig.1).

d) The Sludge Treatment consists of five phases: i) Consolidation: this stage takes place in consolidation and flotation tanks. As the sludge still contains large quantities of water, its volume must be reduced. The consolidation process increases the solid content in the sludge, reducing its volume. This process can increase the proportion of solids from 1% to 5%. In this way, subsequent units, such as digester tanks and drying units have less work to do. The most common methods include gravity consolidation and flotation. Gravity consolidation is based on the principle of zone sedimentation, as in the conventional settling tanks. The consolidated sludge is removed from the base of the tank. Flotation involves the introduction of air in a compression chamber. When the solution is depressurized, the dissolved air forms micro bubbles that carry the clumps of sludge to the surface, where they are removed. ii) Anaerobic Digestion: digestion has the following aims: to destroy dangerous microorganisms, to stabilize unstable substances and organic material present in the crude sludge, reduce the volume of the sludge through liquefaction, gasification and consolidation, to enable the sludge to reduce its liquid level, and to allow the use of the sludge – after stabilization – as a fertilizer or soil conditioner. Without oxygen, only anaerobic bacteria survive, which are able to use combined oxygen. Acidogenic bacteria break down carbohydrates, proteins and lipids, turning them into volatile acids. Methanogenic bacteria convert a large part of these acids into gases, principally methane. The stabilization of these substances can also be performed by addition of chemicals, a process known as chemical stabilization. iii) Chemical Conditioning: chemical conditioning results in the coagulation of solids and the freeing of absorbed water. Conditioning is used before the mechanical drying systems, such as filtration, centrifuging, etc. The chemicals used include iron chloride, line, aluminum sulfate and organic polymers. iv) Press Filters: drying in the press filters occurs under high pressure. The advantages of this system include: high concentration of solids in the sludge cake, low turbidity in the filtrate and high solid retention. The resulting proportion of solids is between 30% and 40% for a 2 to 5 hour filtration cycle – the time needed to fill the press, maintain it under pressure, open it, remove the cake and close the press.

v) Thermal Drying: thermal drying of the sludge is the process of reduction through evaporation of water into the atmosphere by means of heat, resulting in a proportion of solids between 90% and 95%. This reduces the final volume of the sludge significantly (SABESP, 2004).

Figure 2 illustrates the upflow anaerobic sludge blanket (UASB) reactor process, that is an anaerobic treatment system wherein the organic matter is digested, absorbed and metabolized into bacterial cell mass and biogas. Anaerobic digestion is the degradation of organic material without the aid of oxygen.

The UASB process is a combination of physical and biological processes. The main feature of physical process is the separation of solids and gases from the liquid, and that of biological process is the degradation of decomposable organic material under anaerobic conditions.

In the UASB treatment concept, the treatment tank consists of an upflow reactor with feed distribution internal system at the bottom of the reactor and a three-phase separator (gas, liquid, solid) at the top. The wastewater is evenly distributed over the reactor bottom through feed inlet pipes and flows upwards through a bed of anaerobic sludge in the lower part of the reactor called the digestion compartment. During the passage through the sludge bed, particulate matter is entrapped and the degradable matter is completely or partially digested. Dissolved organic matter is removed from the solution by the anaerobic bacteria and converted into biogas and a small fraction into new bacterial biomass. The biogas provides a gentle mixing in the sludge bed. In the upper part of the reactor, a three-phase separator is installed.

The biogas produced is collected in a gas collector (gas holder) from where it is withdrawn. The remaining water sludge mixture enters a settling compartment where the sludge can settle and flow back into the digestion compartment. After settling, the water is collected in the effluent gutters and discharged out of the reactor to the final polishing unit (FPU) to meet discharge standards.

The domestic wastewater treated in an UASB reactor is suitable for discharge in river water or for irrigation after polishing in a high rate pond. The biogas produced can be utilized for generating electricity (National Buildings Construction Corporation Limited, 2005).

The raw and treated sewage composition as well as the sludge composition of Barueri WTP and UASB Reactor is present in Tables 5, 6, 7 and 8, in the appendix.

2.1 COMPARISON BETWEEN AEROBIC (ACTIVATED SLUDGE) AND ANAEROBIC (UASB) TREATMENT

The sewage treatments based on biological processes are most often used, since they enable the treatment of large volumes of sewage transforming toxic organic compounds in carbon dioxide and water (aerobic) or methane (anaerobic). In essence, biological treatment is based on the use of toxic compounds as the substrate for growth and maintenance of microorganisms. Table 1 presents a comparison between aerobic and anaerobic wastewater treatment process (Arvizu, 1996).

Table 1. Comparison between aerobic and anaerobic wastewater treatment process.

Parameter	Anaerobic	Aerobic
Energy requirements	Low	High
Treatment grade	Moderate (60 – 90%)	High (95%)
Production of sludge	Low	High
Stability of the process (to toxic compounds and overloads)	Low to moderate	Moderate to high
Time to startup	2 to 4 months	2 to 4 weeks
Odor	Potential problems	Minor possibility
Nutrient requirements	Low	High for certain industrial wastes
Alkalinity requirements	High for certain industrial	Low
Production of biogas	Yes	No
Investment cost (US$/capita)	30	50
Operating cost (US$/capita)	0.4	0.8 - 1

3. ENVIRONMENTAL EXERGY ANALYSIS OF WASTEWATER TREATMENT PROCESSES

3.1 Environmental impact exergy based index

The environmental impact of the wastewater treatment process is done by means of evaluating the values of the environmental exergy efficiency ($\eta_{env,exerg}$) as proposed by (Makarytchev, 1997; Mora and Oliveira, 2004). The environmental exergy efficiency is defined as the ratio of the final product exergy (or useful effect of a process) to the total exergy of natural and human resources consumed, including all the exergy inputs. That ratio is also an indication of the theoretical potential of future improvements for a process. The environmental exergy efficiency is calculated according to Eq. (1).

$$\eta_{env,exerg} = B_{product} / (B_{Nat,Res} + B_{Prep} + B_{Deact} + B_{Disp}) \tag{1}$$

Where: $B_{Deact.}$= exergy of additional natural resources destroyed during waste deactivation [kW]; B_{Disp} = exergy related to waste disposal of the process [kW]; $B_{Nat.Res}$ = exergy of the natural resources consumed by the processes [kW]; B_{Prep} = exergy required for extraction and preparation of the natural resources [kW]; $B_{Product}$ = exergy of the useful effect of a process [kW].

3.2 Exergy evaluation of the environmental impact of the WTP

The analysis of the environmental impact was carried out for the WTP Barueri and UASB Reactor. Based on the data supplied by SABESP (São Paulo Wastewater Treatment Co.) and the Research Centre for Sewage Treatment. (Ginebra, Colombia), an exergy analysis was realized considering operation in steady state conditions and using annual average data of the process. The chemical exergy of organic matter in the wastewater was calculated according to the relation between chemical exergy of organic substance and the COD utilizing the Eq. (2), as proposed by Tai *et al.*, 1986. With $B_{org,mat}$ = chemical exergy of organic matter [kW].

$$B_{org,mat.} = 13.6COD \tag{2}$$

The molecular mass of sewage was assumed as of the substance $C_{10}H_{18}O_3N$, the exergy of inorganic substances for the raw and treated sewage was calculated considering real mixture (activity $\neq$ molar fraction) and 298.15 K as reference temperature. The exergy of sludge was calculated considering ideal mixture (activity = molar fraction), and the exergy flows due biogas and chemicals were calculated according to standard chemical exergy data presented by Szargut *et al.*, 1988. With the information generated by this exergy analysis, the environmental exergy efficiency was determined and compared.

A detailed description of exergy calculations of WTP Barueri are showed in Mora and Oliveira, 2004. In Fig. 3 and Fig. 4, are presented the exergy balances for the two Wastewater Treatment Processes.

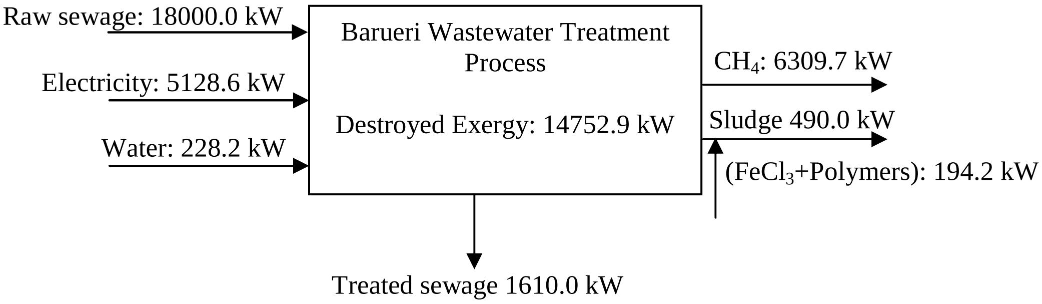

Figure 3. Exergy balance of the Barueri WTP

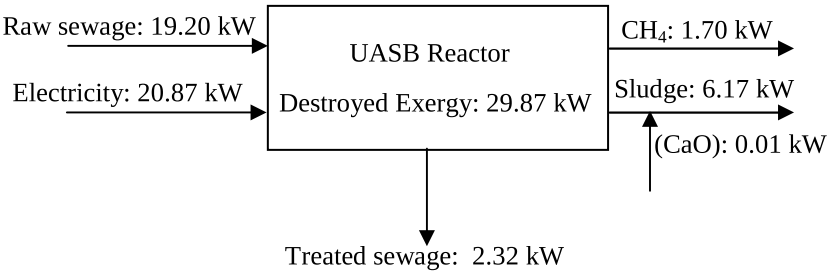

Figure 4. Exergy balance of the UASB Reactor

In Table 2 are presented the values of the input, output, destroyed and lost exergy flowrates and rates for UASB Reactor and Barueri Wastewater Treatment Process.

Table 2. Values of the input, output, destroyed and lost exergy flows for UASB Reactor and Barueri Wastewater Treatment Process.

	Exergy		
Process	Input (kW)	Output (kW)	Destroyed and lost (kW)
UASB Reactor	40.07	2.32	37.75
Barueri WTP	23356.80	1610.00	21746.80

In Table 3 are presented the values of the calculated exergy efficiency based on the results of the exergy balances.

Table 3. Values of the environmental exergy efficiency for the analysed Wastewater Treatment Process.

	Environmental index
Process	$\eta_{env,exerg}$
UASB Reactor	0.058
Barueri WTP	0.069

From the analysis of the results obtained it is observed that if all the exergy associated to the wastes of the process (produced gas and dehydrated mud) was considered as useful exergetic effect (the dehydrated mud for agricultural purposes and the methane as a fuel), the value of the $\eta_{env,exerg}$ for WTP Barueri and UASB Reactor would increase significantly. These values are presented in Table 4.

Table 4. Environmental exergy efficiency for UASB Reactor and Barueri Wastewater Treatment Process considering the use of the produced gas and dehydrated mud.

	Environmental index
Process	$\eta_{env,exerg}$
UASB Reactor	0.255
Barueri WTP	0.368

It is evident that these values must be considered a limiting theoretical condition, because the irreversibilities of the energy conversion processes associated to the use of biogas as a fuel and the use of the mud for agricultural purposes will give a lower value of $\eta_{env,exerg}$.

The organic matter exergy in the raw and treated sewage represent, respectively, for UASB Reactor and Barueri WTP, 97.4% and 91.8%; and 92.8% and 65.2% of the exergy flowrate.

The exergy of the methane produced in the UASB Reactor and Barueri WTP, is 9.1% and 37.8% of the organic matter exergy comprised in the raw sewage. According to Hellström (1997), with techniques used today, about 40% of the exergy of the organic matter can be collected through anaerobic digestion of wastewater solids.

4. CONCLUSION

The environmental exergy efficiency is a suitable indicator for ecological evaluation because it presents a unified thermodynamic measure for objectively evaluating resources utilization, quality of energy conversion processes and environment impact. This relation must be used for determining the most energy efficient system among various chemical and biological wastewater treatment processes**.**

The organic matter exergy in the raw and treated sewage represent, respectively, for UASB Reactor and Barueri WTP, 97.4% and 91.8%; and 92.8% and 65.2% of the exergy flowrate.

The low values obtained for the environmental exergy efficiency are due to exergy destruction in the anaerobic and aerobic processes.

The exergy efficiency identifies the technical inefficiencies in the conversion of organic matter in sewage flows, and highlights clearly that the technology used to utilize the organic matter in sewage is far from being optimized. This is because the technical solution has not considered the recovery of exergy from organic matter as an important aspect. According to Hellström (2003), if a urine separation system was included in the wastewater treatment plant, the nutrients exergy recovery could be improved with a consequent increase of the environmental exergy efficiency.

To complement this work, it is proposed to include a thermoeconomic analysis in the methodology presented for the environmental evaluation of wastewater treatment processes.

5. ACKNOWLEDGEMENTS

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7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.

8. APPENDIX

Tables 5, 6, 7 and 8 present the raw and treated sewage composition as well as the sludge composition of Barueri WTP and UASB Reactor.

Table 5. Composition of the raw and treated sewage for Barueri WTP.

	Composition (mol L^{-1})	
	Raw sewage	Treated sewage
COD	2.30E-03	3.01E-04
NH_3	1.83E-03	5.80E-04
NO_3	2.42E-06	1.11E-04
NO_2	2.01E-07	3.50E-06
S_2	1.60E-05	1.60E-05
SO_4	4.53E-04	3.30E-04
Cd	6.23E-08	4.00E-08
Ni	1.21E-06	6.81E-07
Ag	1.11E-07	3.71E-08
Zn	6.73E-06	1.62E-06
Mg	1.70E-06	1.30E-06
Mo	2.08E-07	2.08E-07
Pb	1.26E-07	7.40E-08
Cu	1.42E-06	2.72E-07
Cr	2.40E-06	6.15E-07
Fe	5.91E-05	8.43E-06
Alcohol	2.34E-06	3.61E-07
P	1.65E-04	7.75E-05
Detergent	5.40E-04	3.25E-05
Sn	1.20E-06	1.10E-06
Overall	5.39E-03	1.47E-03

Table 6. Sludge composition of Barueri WTP.

Components	Composition (mol kg^{-1})
Cd	1.30E-04
Pb	9.70E-04
Cu	9.50E-03
Cr	1.40E-02
Mg	5.50E-03
Fe	6.00E-01
Ni	5.30E-03
Zn	3.54E-02
Ag	5.60E-04
Mo	2.10E-04
Overall	6.72E-01

Table 7. Composition of the raw and treated sewage for UASB Reactor.

	Composition (mol L^{-1})	
	Raw sewage	Treated sewage
COD	3.34E-03	9.15E-04
$CaCO_3$	5.88E-03	5.68E-03
NO_2	1.47E-07	7.30E-07
Cl	1.77E-03	1.66E-03
SO_4	1.94E-03	2.60E-04
Overall	1.29E-02	8.51E-03

Table 8. Sludge composition of UASB Reactor.

Components	Composition (mol kg^{-1})
Ca	1.10E-04
Mg	3.81E-05
K	3.99E-04
Na	1.02E-03
P	5.62E-03
B	1.32E-04
Cu	4.68E-03
Zn	5.37E-03
Mn	3.20E-03
Fe	7.89E-03
Overall	2.85E-02