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Influence of biogas-induced mixing on granulation in UASB reactors

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ABSTRACT

Studies have been carried out to correlate biogas-induced mixing and granulation in upflow anaerobic sludge blanket (UASB) reactors, treating low-strength as well as high-strength biodegradable wastewaters. A dimensionless granulation index (GI) has been framed taking into account the mixing in sludge bed due to produced biogas. Analysis of full-scale, pilot-scale and lab-scale UASB reactors treating actual wastewaters reveals the significance of biogas-induced mixing, represented by GI, on granulation of biomass in the reactors. For obtaining proper granulation in UASB reactors (percentage granules greater than 50%, w/w), resulting in higher chemical oxygen demand (COD) removal efficiency, it is recommended to maintain GI values in the range of 15,000–57,000.

1. Introduction

Anaerobic granular sludge is a dense microbial community inclusive of millions of different micro-organisms. Biomass granulation, exploited in biological wastewater treatment, refers to a process in which microbial aggregates are cultivated to remove biodegradable organic matters and other nutrients. This self-immobilization of microbes is probably best recognized in the upflow anaerobic sludge blanket (UASB) reactors, wherein anaerobic granules have been used for treating variety of wastewaters. Granulation occurs without reliance on artificial surfaces for biofilm attachment, rendering carrier material unnecessary.

Several models have been developed over the past 20 years on the mechanisms of anaerobic granulation. These models mainly include inert nuclei model, divalent cation-bridge model, proton translocation–dehydration model, extra cellular polymer model, spaghetti model, syntrophic micro-colony model, thermodynamic models, etc. [1]. The above models have the ability to explain certain phenomena during the sludge granulation process under specific laboratory conditions. However, each model considers only the role of one or two leading factors involved in the granulation process. These factors usually exert their influence only under specific environmental conditions and in specific step during the whole granulation process. Often, experimental results conducted under different environmental condition contradict these models. For example, it was reported that the granules could be developed without addition of any inert materials [2] and that calcium ion did not induce sludge granulation [2,3].

Alphenaar et al. [4] reported that biomass granulation in an UASB reactor is favored by the combination of high-liquid upflow velocity and short hydraulic retention time (HRT). However, for successful start-up and stable operation of UASB reactors, the reactor HRT cannot be reduced below 6 h. For wastewaters where granulation is reported to be successful, mixing developed in the reactor is of immense significance [5]. In UASB reactors, hydrodynamic shear force, resulting from mixing in the sludge bed, is mainly exerted due to superficial biogas production and liquid upflow velocity [6–8].

Granulation in UASB reactors depends upon several parameters such as wastewater types [9–11]; seed sludge characteristics [12]; characteristics of cell surface [13]; temperature [14–15]; pH [16]; and organic loading rates [4]. However, under favorable wastewater types and environmental conditions, the success of granulation in the reactors for treating biodegradable organic wastewaters (free from toxicity) depends on the operating conditions, defining magnitude of mixing in the reactors.

Although, the functioning of UASB reactor depends on both physical parameters and biological processes, representation of the mixing due to induced biogas has been barely reported in the literature. The role of upward movement of biogas on anaerobic biomass granulation and how one can optimize this factor for obtaining

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granules in UASB reactors has not yet been fully studied. Thus, there is an increasing need to define favorable mixing inside the reactors, which will correlate granulation in UASB reactors when operational and environmental parameters are maintained favorable for growth and proper functioning of anaerobes. The mixing conditions in the UASB reactor can be defined by developing mathematical index considering velocity gradient developed in the reactor under different operating conditions. Hence, development of a dimensionless mathematical index, considering the major parameters responsible for mixing, is felt appreciable to predict granulation in UASB reactor. Thus, the present study aims to formulate a dimensionless index to correlate biogas-induced mixing and granulation in lab-scale UASB reactors.

2. Materials and methods

Two identical UASB reactors (R1 and R2), made of Plexiglas having effective volume 12.57 l, internal diameter 100 mm, and effective height 1.6 m were used in the study. Synthetic wastewater used in this study mainly consists of 0.89 g sucrose, 1.5 g $NaHCO_3$, 0.318 g NH_4Cl, 0.064 g $MgSO_4$, 0.035 g K_2HPO_4, and 0.009 g KH_2PO_4 per gram of chemical oxygen demand (COD). Trace metals (Fe, Ni, Mn, Zn, Co, Cu, and Mo) were added as per the composition suggested by Ghangrekar et al. [17]. The reactors were inoculated with sludge collected from the bottom of a septic tank.

2.1. Analytical techniques

Chemical oxygen demand of effluent sample, suspended solids (SS) in effluent and sludge were determined as per Standard Methods [18]. Total biogas production was measured by water displacement method using distilled water by adjusting pH to 3 by adding 1 N H_2SO_4 and using methyl red indicator. Sludge samples from the reactors were analyzed for SS, settling velocity, specific gravity, and specific methanogenic activity (SMA) after 60–65 days of operation. SMA and settling velocity of sludge was determined as suggested by Ghangrekar et al. [17]. The amount of sludge settled at bottom of settling column was collected after fixed time intervals (0.5, 1.0, 2.0, 3.0, 5.0, 7.0, 15.0, 30.0, and 60.0 min), and SS was determined for each sample to represent the fraction of settled sludge.

2.2. Fractional distribution of different size of granules

Settling velocity of sludge settled at bottom of the settling column after fixed time intervals was considered to determine corresponding size of biomass fractions as per Bhunia and Ghangrekar [19]. Settling velocity of sludge settled at the bottom of the settling column after fixed time intervals (0.5, 1.0, 2.0, 3.0, 5.0, 7.0, 15.0, 30.0, and 60.0 min) was considered to determine corresponding size of the biomass fractions, using Sedimentation theory as suggested by Bhunia and Ghangrekar [19]. From the percentage fractions of the settled sludge at different time intervals, percentage mass fraction of different diameter granules present in the sludge was calculated. For better retention of granules inside the reactor, based on Reynolds number and settling velocity, diameter of bio-particles ≥0.34 mm should be considered as minimum size of granules having specific gravity of 1.035. Likewise, 0.41, 0.36, 0.33, and 0.3 mm are considered as minimum size of granules for sludge having specific gravity of 1.02, 1.03, 1.04, and 1.05, respectively [19]. Percentage of granules in the sludge is expressed as the cumulative percentage weight fractions of particles equal to and above the minimum diameter of granules required for corresponding specific gravity of sludge.

Table 1
Reactors geometry, operational parameters, and percentage granules at different lab-scale experiments

Experiment nos.	A (m^2)	L_b (m)	ν (m^2/s)	X_c (kg SS/m^3)	ρ_s (kg/m^3)	V (m/s)	Biogas production rate (m^3/s)	OLR (kg COD/m^3 s)	Q	% Granules of the total sludge	Remark
1	0.00785	0.42	1.004×10^{-6}	118.56	1035	1.37×10^{-5}	1.37×10^{-5}	2.04×10^{-5}	0.247	58	
2	0.00785	0.465	0.801×10^{-6}	120.40	1035	3.54×10^{-5}	3.54×10^{-5}	4.12×10^{-5}	0.318	79	
3	0.00785	0.24	1.004×10^{-6}	110.72	1058	4.72×10^{-5}	4.71×10^{-6}	1.08×10^{-5}	0.085	37	
4	0.00785	0.2	1.004×10^{-6}	110.72	1040	3.59×10^{-5}	3.59×10^{-6}	1.08×10^{-5}	0.065	35	
5	0.00785	0.31	0.9×10^{-6}	135.69	1040	1.53×10^{-5}	1.53×10^{-5}	2.04×10^{-5}	0.275	56	Present experiment
6	0.00785	0.35	0.9×10^{-6}	135.69	1035	1.52×10^{-5}	1.51×10^{-5}	2.19×10^{-5}	0.202	65	
7	0.00785	0.37	0.801×10^{-6}	110.69	1030	1.22×10^{-5}	1.22×10^{-5}	2.19×10^{-5}	0.110	62	
8	0.00785	0.32	0.801×10^{-6}	110.69	1020	1.06×10^{-5}	1.06×10^{-5}	2.19×10^{-5}	0.095	54	
9	0.01	0.172	0.9×10^{-6}	42.96	1030	6.11×10^{-4}	6.1×10^{-4}	3.44×10^{-5}	44.0	42	
10	0.01	0.268	0.9×10^{-6}	90.545	1024	1.11×10^{-3}	1.1×10^{-3}	11.0×10^{-5}	79.9	63	
11	0.01	0.441	0.9×10^{-6}	64.38	1020	2.11×10^{-3}	2.1×10^{-3}	3.43×10^{-5}	50.6	64	
12	0.01	2.266	0.9×10^{-6}	41.12	1020	6.67×10^{-3}	6.7×10^{-3}	5.65×10^{-5}	160	65	Ghangrekar [31]
13	0.01	0.458	0.9×10^{-6}	30.575	1020	3.0×10^{-3}	3.0×10^{-3}	4.72×10^{-5}	108	64	
14	0.01	0.587	0.9×10^{-6}	77.33	1020	3.0×10^{-3}	3.0×10^{-3}	4.50×10^{-5}	108	78	
15	0.01	0.612	0.9×10^{-6}	92.455	1020	2.94×10^{-3}	2.9×10^{-3}	4.79×10^{-5}	106	65	

Note: Experiment nos. 1–8 were carried out in UASB reactor with circular cross sectional area, whereas 9–15 were carried out with square cross-sectional area.