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Granules as Precursors in the Working of Upflow Anaerobic Sludge Blanket Reactor: A Review on the Impacts of Granulation

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Abstract: High-rate anaerobic digesters are of great concern these days—due to their high loading capacity, reduced carbon footprints and lower sludge production. Among them, the most preferred is the upflow anaerobic sludge blanket (UASB) reactor. However, there are still unresolved issues that inhibit the widespread of this technology. To start with the granular sludge bed fostering the microflora forms the prime seat in the working of UASB reactors. These microflora have a predominant role in the treatment of wastewater, hence the factors governing their growth, survival, and distribution are to be studied. Thus it seemed as due important to analyse the granular sludge for its particle size, particle density, and microfilm characteristics, to enhance the reactor's efficiency. This has made scientists across the world put an eye on factors that shape the granules and how the granules contribute to wastewater treatment. The state-of-the-art is presented in this study.

Key words: Anaerobic reactors, biogas, granulation, microbes, sludge bed, UASB.

Introduction

India being a developing country is in the phase of rapid industrialisation and urbanisation. This is well evident from the agglomeration in urban population from 28 crores in 2001 to 37 crores in 2011 (taken from Census, 2011). Though both are good on one hand with respect to our economic developments, it has indeed put a threat to the goal of sustainable development (Aishwarya Lakshmi & Palanivelu, 2022). Urbanisation has imposed intense pressure on our water resources in two major tracks. Rise in water demand to meet the domestic requirements and discharge of this used water into the receiving environment. To satisfy the growing demand, water for domestic and industrial needs is tapped from rivers streams, wells, lakes, and various ground water resources. Of which 80% of the supplied water for domestic needs returns as wastewater, depleting the water bodies (Sangamnere et al., 2023; Venkatesan et al., 2019).

According to the CPCB reports (2021), nearly 1,631 STPs operate in different parts of our country with a total capacity of 36,668 MLD. Surprisingly the quantity of sewage generated by urban localities was estimated to be 72,368 MLD (nearly double the capacity of treatment plants). Though there are many treatment schemes that are strategically planned and are in place, there is always a large gap between the quantity of sewage generated and the capacity of treatment plants. Hence alarming issue faced by every developing/underdeveloped country would be the discharge of untreated or partially treated municipal sewage into water bodies. Having finite resources in hand, the only sound option to meet our demands would be the conservation of the existing

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aquatic ecosystem (Lakshmi & Raj, 2022). Municipal sewage in other ways, can be considered as a resource to meet our non-portable requirements (Arivalagan & Stanislaus, 2022; Mazhar et al., 2021) by which the groundwater and surface water resources can be conserved.

Among the high-rate systems, the granule-based UASB reactors have been regarded as the most robust technology for the treatment of various high-strength wastewaters. Granules that emerge by the typical aggregation of biomass lay as the soul of this treatment scheme (Sethi et al., 2023). These granules have enhanced settling characteristics which prevent biomass washout (Dignac et al., 1998) also they are capable of providing intimate contact between the microbes and organic matter, which enhances the treatment. Biogas released during the anaerobic digestion aids with the natural turbulence, thus eliminating the need for mechanical devices (Yasar et al., 2007). In addition, anaerobic granular systems are fine-tuned for fluctuations in temperature, pH, influent concentration as well as high salinity. Hence UASB reactors can be coined as energy-economic systems, as they are distinct in forming their own sludge bed.

UASB technology has proven good for high-strength industrial waste waters compared to domestic sewage. The reason behind the shortfall is that – the high suspended solids concentration of domestic sewage generally lengthens the hydrolysis process. Furthermore, the lower organic content is due to decreased methane output, which results in poor mixing and the creation of localised channels in the granular bed (Chang et al., 2006). As a result, low-quality effluent is produced. Another major drawback seems to be the extremely long start-up period (time taken for the formation of the granular sludge bed) of nearly 3-8 months (Zhou et al., 2007). In order to shorten this phase, the mechanism of anaerobic granulation has to be clearly understood, which is critically reviewed in this paper.

The Upflow Anaerobic Sludge Blanket Reactor

The reactor consists of two parts – a cylindrical or rectangular column at the bottom supporting a gas-liquid-solid separator on top. To begin with, the UASB reactor is seeded with inoculum such as digested granular or flocculent sludge at the bottom. After a period of nearly (2 to 8 months), based on the operating conditions and the characteristics of the wastewater and the seed sludge, a very dense sludge bed gets formed. This sludge bed may be granular or flocculent in nature with high settling properties (Guo et al., 2022). Wastewater to be treated is introduced from the bottom of the reactor and it flows upward through the biologically activated sludge bed. This remains as the reaction zone of the UASB reactor, where the actual process of anaerobic degradation takes place. The biogas (methane and carbon dioxide) produced under anaerobic conditions cause internal mixing, which helps in the formation and maintenance of biological granules. The produced biogas and the sludge particles as they rise, are separated from the effluent by the immersed GLSS facility (Sankar Ganesh et al., 2007). On reaching the GLSS, the gas-surrounded particles strike the bottom of the baffles and fall back into the sludge blanket and the treated water flows out of the reactor.

The Importance of Granulation in UASB Reactors

Sound knowledge of the mechanisms responsible for anaerobic granulation is inherent, as it serves as the prime seat for the fruitful operation of granular sludge-based treatment systems. A number of models have been propounded on anaerobic granulation which includes-thermodynamic models, hydrophobic interaction and local dehydration models, surface tension model, inert nuclei model, structural models, divalent cation-bridge model, crystallised nuclei formation model, syntrophic micro colony model, ECP bonding model, The Capetown model, Spaghetti' theory, Proton translocation–dehydration theory and so on (Quarmby & Forster, 1995).

The sludge bed is where the microflora are anchored in such a way, that they get in contact with the organic matter of incoming wastewater, paving to treatment in UASB systems. A typical granule can be portrayed as a veritable micro ecosystem harbouring millions of organisms per gram of biomass (Sethi et al., 2023).

Associations between the component microbes of this ecosystem are mandatory since these species as individuals cannot completely degrade the influent wastes. The vitality of microbial films, shape size and density of sludge particles altogether contribute to the efficacy of treatment (Nuntakumjorn et al., 2008). The granulation process is of utmost importance because the granules besides supporting the biofilm provide the required buoyancy and settleability, needed for granule-liquid contact in the reactor.

To start with the UASB reactor is seeded with anaerobic sludge and wastewater is made to flow in the upward direction through it. Granules start slowly emerging under appropriate conditions of substrate and nutrient availability, pH, alkalinity, up-flow velocity, etc. Due course different syntrophic groups come together to form roughly spherical shaped clusters as depicted (in Figure 1); these clusters have come to be called granules (Morgan et al., 1990). The size of granules may range from 0.1 to 5 mm, with higher shear strength and better-settling properties than flocculated sludge. These granules notably reduce inter-species mass transfer limitation between the syntrophic groups and allow for higher loading rates, with improved resistance to shocks and toxins compared to the dispersed microbes (Lettinga & van Velzen, 1974).

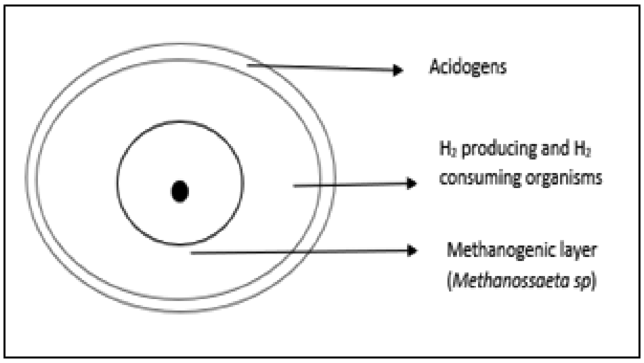

Figure 1: Layered structure of UASB granules.

Granules are often depicted by concentric layers of quite spherical biofilms, occupied by different bacterial trophic groups as shown in Figure 1. Each group has a specific role in the degradation process, producing biomass and ECPs in its vicinity.

Among the microflora, methanogen *Methanosaeta consilii*, is believed to play a key role, by functioning as the nucleation center that initiates granule development. Followed by the subsequent colonisation of acetogenic bacteria and hydrogenotrophic methanogens, which contributes to the layered granular biofilm structure reported by several authors (Liu & Tay, 2004). In contrast, bio hydrogen UASB reactors have granules of a simpler matrix comprising mainly of hydrogen-producing acidogens. As acidogens grow quickly, the formation of these granules is much quicker than that of methanogenic granules (Owusu-Agyeman et al., 2021).

Characteristics of Anaerobic Granules

Microstructure

Makni et al. (2006) have proposed models which suggest that the granule is composed of different layers with the acidogenic bacteria primarily dominating the outer layer, and the inner layer comprising of Methanothrix – like bacteria; serving as the nucleation centers for the initiation of granule development, while H_2-producing and H_2-utilising bacteria are predominant in the middle layer. Some granules with uniform structure were also observed (Grotenhuis et al., 1991). Interestingly, different types of granules were formed for the same substrate, indicating the fact that granular microstructures are dependent on the degradation kinetics of the substrates, i.e. different dominating catabolic pathways might give rise to different granules (Liu & Tay, 2002; Schmidt & Ahring, 1994).

Surface Properties

The microbial cell surfaces are generally hydrophobic in nature which keeps them self-immobilised and dense. With the application of selection pressure by the high up-flow velocity, the microorganisms having hydrophobic surfaces can be easily self-immobilsed to form denser aggregates to remain in the reactors.

With reference to thermodynamics, increasing the hydrophobicity of cell surfaces might cause a decrease in the excess Gibbs energy of the surface, leading to higher cell-to-cell interactions which would result in a stable structure. Environmental conditions such as starvation, oxygen level and liquid ionic strength can change the hydrophobicity of cell surfaces (Ramakrishnan & Gupta, 2006). Under normal pH conditions, the surface of microorganisms is negatively charged. Quarmby & Forster (1995) have suggested that granules tend to become weaker as the surface negative charge increases. Schmidt & Ahring (1994) and Venkatesan et al. (2023c, d) have made an observation that the maximum self-immobilisation strength was visualised in the isoelectric point of cells. Thus it can be concluded that the anaerobic granulation is closely correlated to the surface properties of sludge.

Factors Influencing Granulation

Effect of pH and Alkalinity

The acidogenic microbes are less susceptible to pH fluctuations when compared to methanogens. To obtain a good quality granulated sludge, the pH of the reactor must be maintained at nearly neutral conditions in the range of 6.3 to 7.8. At times if the volatile fatty acids concentration exceeds the buffering capacity of the reactor contents, then the pH of the reactor drops to the acidic range. At lower pH conditions the acidogenic microbes are much more productive than the methanogens, which may lead to the disintegration of the granules (Jia et al., 1996).

Alkalinity bestows buffering capacity to a UASB reactor. Fluctuations in the VFA concentration, which arise due to the variation in organic loading rates are neutralised by alkalinity. Thus, the interplay between alkalinity and chemical oxygen demand (COD) has an impact on granulation. Alkalinity levels ranging between 250 and 950 mg/L are considered favourable for the formation and stability of granules.

Role of Extracellular Polymers

Extracellular polymers secreted by the microbial cells and exposed at their surfaces under suitable physiological conditions pose a vital role in the granulation process. ECP materials help to adhere and connect the flocculent sludge particles together by their position and chemical properties. Earlier studies have also indicated that with plentiful foodstuffs, microorganisms were stimulated to produce more ECP in a relatively shorter time because of their increased anabolic activity. Works by Zhou et al. (2007) have outlined that when substrates like glucose and skim milk were added to the feed, the startup phase had shortened owing to enhanced granulation. Also with slight overloading ECP production was promoted which confirmed that ECP served as the driving force for granulation.

However excessive levels of ECP do not favour granulation and may even unhinge the granules formed. ECPs isolated from cells cultivated separately and added externally at the startup had no beneficial effects on granulation; rather they were seen to exert an inhibitory effect (Schmidt & Ahring, 1994).

Summary and Conclusion

Of all the high-rate anaerobic reactors UASB accounts for nearly 80% of the world's anaerobic wastewater treatment systems. It is the sludge bed with the anchored microflora, which serves as the principal component of the treatment process. Under optimised conditions of feed strength, nutrient supplementation, reactor hydraulics and other factors, the sludge particles get transformed to stabilised granules, with better settleability even under shock load conditions.

In-depth, assessment of the past works on the mechanism of granulation, factors affecting granulation and to what extent they influence the treatment efficiency can be collectively stated as:

1. Optimum alkalinity is mandatory to maintain the reactor pH and to buffer the system for significant fluctuations in the VFA concentrations.
2. Microflora are highly susceptible to temperature changes and the granule composition also differs with temperature variations.

To conclude the biggest challenge of UASB technology can be the enhancement of start-up phase. Though there are a number of works favouring this, many are limited to lab-scale applications. Also, the works stated have focussed mainly on the positive or negative effects of various parameters on granule development. But the gap mainly falls in drawing the boundary between these parameters as to what exact range would suit all substrates, operating conditions and reactor capacities.

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