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Review

# Applicability and trends of anaerobic granular sludge treatment processes

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ABSTRACT

Anaerobic granular sludge treatment processes have been continuously developed, although the anaerobic sludge granulation process was not clearly understood. In this review, an upflow anaerobic sludge blanket (UASB), an expanded granule sludge blanket (EGSB), and a static granular bed reactor (SGBR) were introduced as components of a representative anaerobic granular sludge treatment processes. The characteristics and application trends of each reactor were presented. The UASB reactor was developed in the late 1970s and its use has been rapidly widespread due to the excellent performance. With the active granules, this reactor is able to treat various high-strength wastewaters as well as municipal wastewater. Most soluble industrial wastewaters can be efficiently applied using a UASB. The EGSB reactor was developed owing to give more chance to contact between wastewater and the granules. Dispersed sludge is separated from mature granules using the rapid upward velocity in this reactor. The EGSB reactor shows the excellent performance in treating low-strength and/or high-strength wastewater, especially under low temperatures. The SGBR, developed at Iowa State University, is one of anaerobic granular sludge treatment processes. Although the configuration of the SGBR is very simple, the performance of this system is similar to that of the UASB or EGSB reactor. The anaerobic sludge granulation processes showed excellent performance for various wastewaters at a broad range of organic loading rate in lab-, pilot-scale tests. This leads to erect thousands of full-scale granular processes, which has been widely operated around the world.



## 1. Introduction

Anaerobic treatment is the history of wastewater treatment itself. Jewell [1] stated that a septic tank is the simplest, oldest, and most widely used process. Anaerobic treatment has been rapidly developed since the late 1960s. Anaerobic digestion has been used to treat industrial wastewaters as well as domestic wastewater for decades [2–6]. Anaerobic treatment of organic compounds has many advantages over aerobic treatment. Anaerobic treatment requires low energy consumption and low macro/micro-nutrients and provides low waste biological solids. It is expected that excellent performance at a high loading rate and the improved dewaterability

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after anaerobic treatment. In addition, anaerobic treatment is the capacity of a storage unfed for several months and generates biogas. However, anaerobic treatment has to overcome some disadvantages such as process sensitivity, vulnerability, odor problems, the requirement of a long start-up period, and post treatments for discharge standards. Several investigators researched anaerobic digestion of toxic or xenobiotic compounds [5,7,8]. When starting up full-scale anaerobic treatment processes, the sufficient inoculation must be provided to overcome these drawbacks. Lettinga [8] reported that an anaerobic digestion process generates ions such as ammonium, phosphate, or sulfide, and requires additional post treatments for the sustainable environmental protection. For odor problems, physicochemical or biological processes can effectively prevent odors arising from anaerobic digestion [8]. In fact, anaerobic digestion is a very stable process if operating parameters are sufficiently understood [2,9]. Since Young and McCarty [10] first developed the anaerobic filter (AF), several investigators have developed high-rate anaerobic digesters. In the Netherlands, the upflow anaerobic sludge blanket (UASB) reactor was developed in the late 1970s, and was later modified or combined with other process to treat various types of wastewater [8,11,12]. Specifically, the modified UASB reactors were used to treat recalcitrant organic matter and/or solids in the influent [13,14]. Chernicharo and Machado [15] treated municipal wastewater using a UASB/AF system. According to their results, the removal efficiency of biochemical oxygen demand (BOD) was 95% and the concentration of suspended solids (SS) in the effluent was kept below 25 mg $L^{-1}$. Alrajoula et al. [13] showed that the AF can efficiently polish SS from the UASB effluent. The objectives of this review article were to compare the characteristics and performance between the UASB and expanded granule sludge bed (EGSB) reactors, and to present not only application to various types of wastewater but also research trends of each reactor. In addition, the information about anaerobic sludge granulation and the static granular bed reactor (SGBR), one of modified UASB reactors, were discussed in this review.

## 2. Anaerobic sludge granulation

Anaerobic sludge granulation is quite complex and is affected by many physicochemical parameters. Although several hypotheses have continuously been made regarding the granulation process in various anaerobic digesters, the granulation process is still not clearly understood [16–19]. Most microorganisms that are able to form granules can be classified as denitrifying bacteria, nitrifying bacteria, acidifying bacteria, and/or methanotrophs. However, the characteristics of anaerobic granules can be affected by several parameters such as the species of organisms and the growth/decay rate of organisms in granules [8]. Nicolella et al. [20] showed a concentration-flow rate diagram for application of floc and biofilm reactors (Fig. 1). As shown in Fig. 1, anaerobic granular sludge can be maintained under high strength and low flow rate conditions of wastewater. In other words, anaerobic granular sludge reactors can treat high-strength organic wastewaters without recirculation or external separation.

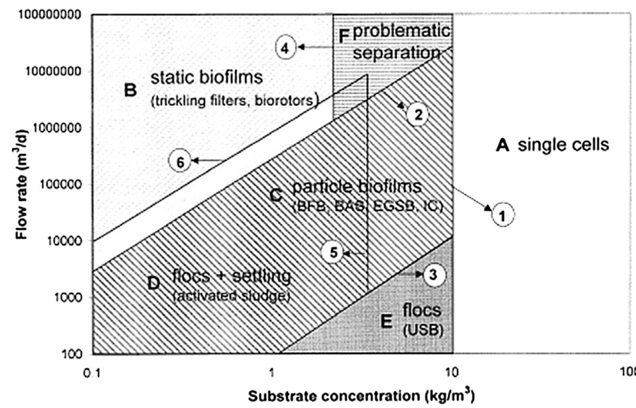


**Fig. 1 – Concentration-flow diagram for sludge granulation [20].**

### 2.1. Inorganic composition

The inorganic fraction of anaerobic granules can be severely affected by several parameters such as the composition of wastewater and process conditions. The ash content in the granules grown on a complex wastewater was lower than that in the granules grown on a simple wastewater such as acetate, propionate, or butyrate. In addition, the sizes of the granules grown on a complex substrate were bigger than those of granules grown on a simple substrate [19,21–27]. When the density of the granules is high, the difference in their shape and/or density under various conditions can be determined since the granules have low porosity. Ash mainly consists of calcium, potassium, and iron [19,24,28–30]. If the ash content in the granules is high, the ash can act as an inhibitor of the transportation of the substrate, gases, and metabolites between the cells and bulk solution. An increase in the ash content results in an increase in the density of the granule. On the other hand, there is no relationship between the ash content and the strength of the granule [25]. Some researchers reported that FeS contributes to a black color [24]. However, Kosaric et al. [31] stated that other parameters might be of more importance in creating the black color of the granules.

### 2.2. Extracellular polymer substances

Extracellular polymer substances (EPS) play very important roles in forming and maintaining anaerobic granules. EPS mainly consist of polysaccharides, proteins, lipids, phenols, and nucleic acids. They also contain organic debris, phages, and lysed cells [32]. It is well known that the surface charge of microorganisms is commonly negative. This implies that positive charges or EPS/polymers are required to form stable granules. Zhou et al. [33] showed that the EPS content and surface charges of substrates are very important when forming granules based on the Derjaguin–Landau–Verwey–Overbeek (DLVO) theory in a UASB reactor. Several investigators presented that EPS can protect bacteria from the surroundings, and that the interaction with the granules contributes to the sludge granulation [24,34,35]. The organic content of the EPS ranges approximately 0.6%–20% of volatile suspended solids,