Anaerobic Digestion of Domestic Wastewater: The Role of Alkalinity in the Rate and Extent of Digestion

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Abstract: For an anaerobic baffled reactor (ABR) treating domestic wastewater, the major variables affecting the rate and extent of digestion are the organic loading/residence time, the upflow velocity and the pH/alkalinity characteristics of the wastewater. In this study, an ABR was operated at two different flow rates; in Phase A, a higher loading rate of 0.74 kgCOD/m³.d was employed, while in Phase B, the loading rate was reduced to 0.40 kgCOD/m³.d. At the higher organic loading rate, significantly higher solids accumulation rates per kgCOD treated were obtained, and it was estimated that only 30% of the influent COD was converted to CH4. At the lower loading rate the estimated conversion to methane was 60%.

The most probable cause for the poor COD removal was failure of stable anaerobic microbial consortia to establish under the relatively high selection pressure experienced at the high loading rate, due to washout of anaerobic species. It was concluded that low wastewater alkalinity (240 mgCaCO3/l) characteristic of the KwaZulu-Natal East Coast region resulted in low compartment pH values and associated inhibition of microbial activity, causing slower digestion of organics, and greater washout, particularly of methanogenic organisms, at higher up-flow velocities. The implication was that critical value for up-flow velocity, above which washout of anaerobic species occurs, depends on the organic loading and the prevailing pH and alkalinity.

This has implications for the stability of any anaerobic system, and the extent of treatment of the effluent, specifically, that low wastewater alkalinity has the potential to significantly affect reactor design in any anaerobic system.

Keywords: Anaerobic digestion, domestic wastewater, alkalinity, anaerobic baffled reactor, ABR

INTRODUCTION

The rate, extent and stability of anaerobic digestion processes is dependent on the establishment of a stable microbial community that consists of a range of micro-organisms, each capable of carrying out a step in the process of anaerobically converting the feed material into mineral products and biomass. In general the successful operation of an anaerobic digester for the treatment of a particular feed stream depends on: (i) the presence of a stable, active anaerobic sludge that is conditioned to the feed, and (ii) appropriate conditions for digestion, such as suitable pH, pe, temperature and lack of toxic or inhibitory compounds in the digestion liquors. These conditions are interrelated since the activity of the sludge can in many cases play a role in regulating the pH and concentration of aqueous species, while appropriate aqueous conditions promote biological growth and development of a stable sludge.

Hulshoff Pol et al [1] describe selection pressure in an upflow anaerobic process as the continuous selection of sludge particles on the basis of size, density and structural integrity by the continuous application of hydraulic shear forces from upflow through a granular sludge bed. Upflow results in the washout of light and small granules or granule debris. Selection pressure therefore depends on three things:

- hydrodynamic effects related to particle settling and up-flow velocity;
- microbial growth rate due to feed type, concentration and inhibitory effects.
- Granulation rate, which is a function of hydrodynamics, feed type and loading [2]

This work emanates from a study on the performance of a 3 000ℓ, 8-compartment anaerobic baffled reactor (ABR) treating wastewater derived from a predominantly domestic source [12]. Two hydraulic loading rates were analysed and it was observed that at lower flows, lower effluent COD concentrations and better sludge granulation were observed, while at the higher flow, effluent COD values were higher and poor granulation was observed. All of these results, but particularly the difference in condition of sludge granules obtained at the different flow rates indicated that the two conditions result in different microbial selection pressure in the same system. This paper considers the nature of microbial selection pressure in controlling the rate and extent of digestion in the ABR,
and the particular role that alkalinity plays in the selection pressure. The principles expounded may be generalised to other anaerobic up-flow systems.

THEORY

An ABR consists of a series of compartments or tanks where the overflow from one tank is supplied to the bottom of the next compartment, either by down-comer pipes, or a down-flow section, and then passes through an up-flow section containing a sludge bed or sludge blanket (Figure 1). Sludge is retained in the up-flow compartments by settling of solids against the up-flow of the digestion liquors [3]. Thus the ABR operates as a train of upflow anaerobic sludge blanket (UASB) reactors in series.

![Figure 1: Typical construction of an ABR with (a) downcomer pipes and (b) hanging and standing baffles to create down-flow and up-flow zones.](https://iwaponline.com/wpt/article-pdf/5/4/wpt2010098/382961/98.pdf)

The advantage of this design is that the liquid flow makes repeated passes through the sludge bed, ensuring good contact between liquid and solid and reducing bypassing of the sludge beds [3]. However, the disadvantage is that for a fixed feed flow rate and fixed overall reactor volume, the up-flow velocity in each compartment increases with the number of compartments, since the length of the flow path between digester inlet and outlet increases with the number of compartments that the flow passes through [4].

Granulation processes in anaerobic digestion

The formation of granular sludge has been observed in many anaerobic digestion applications. Granules are complex structures consisting of layers of micro-organisms associated with extracellular polymeric substances (EPS) and in some cases inorganic material that has become embedded in the granule, or that assisted in nucleus formation [2,5,6,7,8]. The presence of granular sludge in upflow anaerobic systems has ensured the success of these systems in high rate removal of organic material as a result of their superior settling characteristics and therefore high sludge retention rates [2,8]. A well-developed and stable granular sludge allows the establishment of high sludge loads in the reactor and maintains micro-organism diversity, even under conditions of high selection pressure [1]. Granulation usually occurs spontaneously, although it may take several months from start-up of an anaerobic system before a stable granular sludge develops. Most authors identify the filamentous acetoclastic methanogenic species *Methanosaeta concilii* as playing a central role in the development of the granule through a number of possible mechanisms [2,5,6,9].

In their review of granulation theories, Hulshoff Pol et al. [2] concluded that granulation is strongly dependent on growth conditions; i.e. by enhancing conditions for growth of anaerobic micro-organisms, the rate and extent of granulation can also be enhanced, and that pH is a key factor in maintaining appropriate digestion conditions.

Alkalinity and pH in anaerobic digesters

A pH range of 6.5 to 8.2 is generally considered acceptable for anaerobic digestion [10], although the effect of pH is different for each of the subprocesses. A simplified view of the reaction sequence is hydrolysis, followed by acidogenesis which tend to lower the pH, followed by...
methanogenesis, which uses the organic acids generated by the preceding steps to produce carbon dioxide and methane, thereby tending to raise the pH. Although these processes are sequential at the molecular level, they take place simultaneously in the mixed reaction environment. However, methanogenesis is particularly sensitive to pH values, exhibiting a rapid decrease in maximum reaction rate when the pH drops below a value of 6.5, or exceeds 8.5.

Bicarbonate alkalinity is therefore a critical factor in controlling the condition of anaerobic digestion. It assists in preventing the digester pH from falling too low during the production of weak acids by the digestion processes. If production of weak acids exceeds the available buffering capacity, the pH of the digester decreases, resulting in inhibition of microbial activity [10]. In most anaerobic systems, the predominant weak acid is CO₂. Thus the main purpose of maintaining a sufficiently high concentration of alkalinity in an anaerobic digester is to buffer carbon dioxide acidity.

Since pH has a strong controlling effect on the growth rate of anaerobic micro-organisms, the alkalinity concentration has an effect on microbial selection pressure. This may be demonstrated by considering granulation rates for (a) a particular organic loading rate and up-flow velocity under conditions where alkalinity is sufficiently high to buffer the pH at values above 7; and (b) where the alkalinity is low and pH values remain below 7; the growth rate and therefore granulation rate will be higher for the well buffered situation (situation a), but relatively lower for the poorly-buffered situation (situation b). Thus for the same hydraulic loading rate and upflow velocity, the microbial selection pressure will be different for different alkalinity and pH conditions.

MATERIALS AND METHODS

The ABR used in this study was constructed from mild steel and had a working volume of 3 m³ with dimensions 3 m × 1 m × 1 m and a constructed height of 1.2 m allowing a headspace height 0.2 m.

The pilot ABR was operated at two hydraulic retention times (Phase A HRT = 22 h and Phase B HRT = 42 h) at Kingsburgh WWTP over a 4 month and a 6 month period respectively. Kingsburgh WWTP treats a wastewater that has no formal industrial effluent component. The average up-flow velocity in each compartment was calculated from compartment dimensions and the average HRT. These values were 0.55 m/h and 0.27 m/h respectively.

The composition of the wastewater fed to the ABR could not be controlled, but was found to be fairly constant over the period of operation with a mean concentration of 680 mgCOD/ℓ. Thus the only variable that could be controlled was the feed flow rate, which fixed the organic load and internal flow velocities within the ABR. Comprehensive data sets (COD, pH, alkalinity, ammonia, solids) in the effluent and within compartments were obtained for operation at two organic loading rates, 0.74 kgCOD/m³.d and 0.40 kgCOD/m³.d. Sludge bed height data within compartments were obtained using a core sampler and recording the height of the sludge bed after 5 min settling time.

RESULTS

The complete set of results obtained from operation of the pilot ABR may be found in [12]. Of interest in this paper are COD removal, alkalinity, pH, and sludge accumulation.

Table 1 shows that the mean outflow COD concentration was significantly lower at low loading rates than at high loading rates. This result implied that the longer retention time of Phase B (42 h) as compared to the Phase A (22 h) resulted in a greater extent of removal (fraction of biodegradable COD converted to CH₄).

Settled sludge bed height is not an absolute indication of the amount of sludge in a compartment since the bulk density of sludge (mass of sludge granules per unit volume of sludge bed) can change significantly according to extent of granulation/dispersion, pH, redox potential, operating conditions and inert content. However, it provides a good visual indication of how the amount of sludge in each compartment varies with time, and how the sludge load varies from one compartment to the next.
Table 1: Inflow and outflow characteristics, for high and low loading rates. Data are presented as mean value ± 95% conf. Interval, [min, max] (number of observations)

<table>
<thead>
<tr>
<th></th>
<th>In High loading rate</th>
<th>Out Low loading rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average HRT</td>
<td>H</td>
<td>22</td>
</tr>
<tr>
<td>Average OLR</td>
<td>kg COD/m³.d</td>
<td>-</td>
</tr>
<tr>
<td>Average upflow velocity</td>
<td>m/s</td>
<td>-</td>
</tr>
<tr>
<td>COD</td>
<td>mg COD/l</td>
<td>680 ± 25</td>
</tr>
<tr>
<td>Alkalinity</td>
<td>mg CaCO₃/l</td>
<td>243 ± 6</td>
</tr>
<tr>
<td>pH</td>
<td></td>
<td>7.1</td>
</tr>
<tr>
<td></td>
<td>(median value reported)</td>
<td>[4, 7.94]</td>
</tr>
</tbody>
</table>

Figure 2 shows the sludge accumulation estimated from the sludge bed height data for low and high loading rates. The volume of sludge was calculated as follows:

\[ V_{\text{s, settled}} = \left( \sum y_i \right) \cdot \left( \text{c/s area of up-flow compartment} \right) = \left( \sum y_i \right) \cdot (w \cdot l) \]

where \( y_i \) is the height of settled sludge in compartment \( i \) and \( w \) and \( l \) are the width and length respectively of the upflow side of each compartment.

A total solids load was calculated for the pilot-scale ABR analogous to the total settled sludge volume:

\[ TS_i = \left( \sum (C_{TS,i} \cdot Y_{i, max}) \right) \cdot \left( \text{c/s area of up-flow compartment} \right) = \left( \sum (C_{TS,i} \cdot Y_{i, max}) \right) \cdot (w \cdot l) \]

Where \( C_{TS,i} \) is the average total solids concentration in a mixed core sample from compartment \( i \), \( Y_{i, max} \) is the maximum height of compartment \( i \) and \( w \) and \( l \) are compartment width and length respectively.

The results of the regressions performed on sludge volume and mass data are presented in Table 2. The regression analysis calculated the probable range of the accumulation rates in m³ settled sludge/year (or kg dry solids/year), and the ratio of the two volumetric sludge accumulation rates calculated using Fieller’s theorem [15].

It was surprising that although the organic loading rate in Phase A was double that of Phase B, the Phase A sludge accumulation rate appeared to be significantly more than double that of Phase B. The ratio of the sludge accumulation rate in Phase A to that of Phase B had a 95% confidence interval of 2.6 to 6.1 i.e. the rate of sludge accumulation in Phase A was between 2.6 and 6.1 times greater than that of Phase B despite the fact that the OLR was approximately double. This may be explained more clearly by presenting the sludge accumulation rate per kgCOD applied to the ABR, as shown in Table 3.

It was expected that the normalised sludge accumulation rate would be higher in Phase B than in Phase A since the lower feed flow rate resulted in lower upflow velocity in the upflow compartments, and this was expected to lead to better sludge retention. However,
Table 3 shows the opposite result; i.e. a significantly lower normalised sludge accumulation rate in Phase B than in Phase A.

![Graph](https://iwaponline.com/wpt/article-pdf/5/4/wpt2010098/382961/98.pdf)

**Figure 2:** Volume of sludge in the upflow compartments of the pilot-scale ABR for (a) high loading rate and (b) low loading rate showing linear regression line with 95% confidence interval on the regression (------). Sludge loss incidents due to washout are indicated by green dashed lines. Three serious sludge loss incidents were reported for high loading rate operation before day 40.

![Graph](https://iwaponline.com/wpt/article-pdf/5/4/wpt2010098/382961/98.pdf)

**Figure 3:** Mass of dry solids in the upflow compartments of the pilot-scale ABR for low loading rate

**Table 2:** Results of regression analysis on solids accumulation in the pilot-scale ABR

<table>
<thead>
<tr>
<th>Loading rate</th>
<th>Calculated quantity</th>
<th>Units</th>
<th>Average slope of regression [Confidence interval on slope]</th>
<th>Significance of regression (P)</th>
<th>No. of observations used in regression</th>
</tr>
</thead>
<tbody>
<tr>
<td>High (Phase A)</td>
<td>Sludge volume</td>
<td>m³ settled sludge/ year</td>
<td>3.46 [2.28, 4.64]</td>
<td>0.00125</td>
<td>6</td>
</tr>
<tr>
<td>Low (Phase B)</td>
<td>Sludge volume</td>
<td>m³ settled sludge/ year</td>
<td>0.901 [0.602, 1.20]</td>
<td>5.87 × 10⁻⁶</td>
<td>20</td>
</tr>
<tr>
<td>Low (Phase B)</td>
<td>Mass of total solids (dry)</td>
<td>kg dry solids/year</td>
<td>60.7 [33.5, 87.8]</td>
<td>2.54 × 10⁻³</td>
<td>17</td>
</tr>
<tr>
<td>High:Low</td>
<td>Ratio of sludge volume slopes: Phase A/Phase B</td>
<td>-</td>
<td>3.84 [2.55, 6.06]</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**Table 3:** Calculation of sludge accumulation rates normalised by organic loading rate

<table>
<thead>
<tr>
<th>Units</th>
<th>Sludge accumulation rate</th>
<th>Organic loading rate</th>
<th>Normalised sludge accumulation rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>m³ sludge/year</td>
<td></td>
<td>kg COD applied / m³ reactor volume, year</td>
<td>t sludge accumulated / (kg COD applied)</td>
</tr>
<tr>
<td>Phase A</td>
<td>3.46</td>
<td>269</td>
<td>4.3</td>
</tr>
<tr>
<td>Phase B</td>
<td>0.901</td>
<td>146</td>
<td>2.1</td>
</tr>
<tr>
<td>Phase B (kg dry solids)</td>
<td>60.7[^109]</td>
<td>146</td>
<td>0.14 [kg dry solids/ kg COD applied]</td>
</tr>
</tbody>
</table>
Figure 4 shows pH and alkalinity profiles measured during Phase A. The alkalinity generated by the digestion is clearly inadequate to counter the drop in pH, which continues across the entire set of compartments. In most compartments the pH was below 6.5, which is considered the lower limit for effective anaerobic digestion.

Mass balance calculations were undertaken to predict the methane yield for Phase A and Phase B, based on the amount of COD in the feed to the ABR, the amount of COD in the effluent, and the amount of COD accumulated as sludge within the ABR. These calculations indicated that while approximately 69% of COD was removed from the wastewater stream by the ABR, only 30% of influent COD was converted to CH$_4$ at the higher flow rate (Phase A). In comparison, at the lower flow rate (Phase B), an overall COD removal of around 81% was obtained, of which, 60% was converted to CH$_4$ [12].

The most obvious explanation for the difference in normalised accumulation rates and in calculated methane yield is that the additional solids accumulated in Phase A were undigested biodegradable particulate material originating from the feed material. The implication is that the resident anaerobic biomass population in the pilot-scale ABR in Phase A was either not sufficiently concentrated or not sufficiently active to digest biodegradable particulates at the rate at which they entered the ABR; while in Phase B, a greater degree of bioconversion of biodegradable particulates was obtained due to the establishment of a more stable anaerobic community at the lower upflow velocities applied in Phase B.

In Phase A, two independent studies on microbial community structure [13,14] showed that acetoclastic methanogenic populations in the pilot-scale ABR at a high loading rate were not well established. This was most clearly shown in the failure to systematically observe *Methanosaeta* spp., in either dispersed sludge or within granules by either SEM [13] or direct molecular techniques [14]. Furthermore, granules were small, few and had a brittle, unstratified structure with a tendency to crumble (Figure 5).

In Phase B, at a flow rate approximately half that of the previous phase, granulation was observed with much larger, two-layered granules that were found to have large populations of Methanosaeta-like micro-organisms present in the granule interior (Figure 6). Much greater microbial diversity was observed than in Phase A. A significant observation was the fact that Methanosaeta-like micro-organisms and granules were not observed in the first compartment at all, but both were found in compartments 2, 3 and 4, with decreasing observations of these micro-organisms in dispersed
sludge of later compartments. This implies that partial phase separation has occurred between the first and subsequent compartments with hydrolysis and acidogenesis predominating in the first compartment and establishment of acetoclastic methanogenesis thereafter.

Figure 5: Scanning electron micrographs showing (a) the surface topology of an entire granule taken from compartment 3 of the pilot-scale ABR during Phase A; and (b) Cleaved granule showing loosely packed, cavity filled structure of the granule interior. (Reproduced with permission from Pillay, 2006)

It was concluded that the small range of methanogenic micro-organisms observed in samples obtained from Phase A was due to limited microbial diversity caused by selection pressure, where environmental conditions preclude the establishment of certain slower growing micro-organisms, which are not able to grow at a rate faster than the washout rate. [13] was able to convincingly show that at the relatively low pH values observed in the pilot-scale ABR and at the relatively high upflow velocities applied in Phase A, a number of factors could have resulted in the failure of Methanoseta spp. in particular to establish in the reactor. This was concluded to have been a significant cause of the little and poor granulation in Phase A.

These results support the hypothesis that high solids accumulation rates in Phase A were caused by the failure to establish a stable granular sludge under the prevailing conditions in Phase A.

As the concentrations of soluble components in the pilot-scale ABR were relatively low during the treatment of domestic sewage, the cause of the differences in population stability between the different flow rates must be the higher upflow velocities employed in Phase A resulting in the washout of anaerobic micro-organisms. Thus it may be concluded that the upflow velocity in each compartment is a critical design factor that must be considered in conjunction with HRT and OLR when sizing a baffled reactor for the treatment of domestic sewage.

Figure 6: Scanning electron micrographs of granules from compartments 2 and 3 harvested from the pilot-scale ABR during Phase B (Reproduced with permission from Pillay, 2006)
DISCUSSION

The analysis of the pilot-scale ABR data concluded that acetoclastic methanogens were not well established, and poor granule formation was observed (assumed to be due to a high washout rate of slower growing anaerobic micro-organisms) at the upflow velocities applied in Phase A; conversely, at the lower hydraulic and OLR of Phase B, good granulation and acetoclastic methanogenesis were both observed. It was shown that the amount of sludge accumulating per kg COD applied was higher in Phase A than in Phase B despite the higher upflow velocities in Phase A, and this was attributed to the much enhanced digestion rates in Phase B due to the establishment of more stable and diverse microbial consortia.

The mean upflow velocities for these two phases were calculated as 0.55 m/h in Phase A and between 0.27 m/h and 0.30 m/h in Phase B (Table 1). In their review of UASB processes, Lin and Yang [16] state that the design of the settling region of a UASB reactor should not exceed a superficial velocity of 0.7 m/h; Sasse [17] recommended a design upflow velocity not exceeding 2 m/h for an ABR treating domestic wastewater and Hulshoff Pol et al. [2] indicated that the settling velocity of anaerobic granules was commonly in the region of 60 m/h i.e. it appears that the performance of the pilot-scale ABR was poor in compared to other anaerobic applications.

The maximum upflow velocity (the lowest upflow value at which acetoclastic methanogens fail to establish due to high selection pressure) is not a fixed value for all systems, but is related to growth rates of micro-organisms and settling properties of the sludge:

- At high growth rates, and particularly when the rate of growth of sludge (in an easily settleable form) is high, higher upflow velocities may be achieved.
- Conditions that cause low microbial growth rates such as low OLRs and low pH conditions (or high concentrations of toxicants) will result in wash-out of slowest growing microbes at lower upflow velocities than in some more highly loaded systems.
- It was noted that the local municipal region, eThekwini, experiences low alkalinity concentrations in water resources and in potable water, and that this is a determining factor in the low reactor pH values observed in this study (Table 1). Thus low inflow alkalinity concentration resulted in low pH values in the reactor, and consequent inhibition of microbial growth. This in turn led to a lower estimation of critical up-flow velocity than may have been inferred in a situation with higher alkalinity waters.
- At low biodegradable COD concentrations, especially low soluble COD concentrations, the development of granules is not favoured since the rate of diffusion of organic substrate into sludge granules is low due to small concentration gradients. The flow rate required to wash out small granules or ungranulated sludge flocs would therefore also be higher, compounding the problem of low growth rates.

In this study, both low OLRs and low pH conditions can be expected to have negatively impacted on microbial growth rates and thus increased the susceptibility to wash-out of slow growing microbes. This explains why poor digestion rates were obtained despite operating at up-flow velocities much lower than recommended in literature.

It is concluded that the ability to treat domestic wastewater at higher OLRs than tested in this study will depend on designing the upflow section of each compartment such that the superficial upflow velocity is below the critical value at which slower growing micro-organisms will not establish. A value of 0.3 m/h for critical up-flow velocity is proposed at the design OLR for low alkalinity applications. Sufficient biomass retention may be achieved at up-flow velocities of 1 m/h or higher if there is no inhibition due to low pH values.

Since microbial respiration rates were limited by low pH values and low substrate concentrations, the critical upflow velocity is not a global value, but system specific and dependent on prevailing pH conditions determined by alkalinity concentration and organic strength of the wastewater to be treated.
This study has indicated that the selection pressure experienced by an anaerobic sludge in an upflow anaerobic application depends on the strength of the wastewater being treated, the alkalinity and pH exerted within the digester and the up-flow velocity in the digester. Therefore it is not possible to reliably design a system for converting wastewater COD to methane on the basis of organic loading rate, hydraulic loading rate or up-flow velocity alone; rather, all three factors should be specified in the design, and the design values will be different for different alkalinity concentrations.

**SUMMARY AND CONCLUSIONS**

- A 3 000ℓ anaerobic baffled reactor was fed domestic wastewater operated at two flow rates (Phase A and Phase B) and COD removal, alkalinity, pH and solids accumulation data were obtained.
- The rate at which solids accumulate (considering only the upflow side of each compartment was found to be 2.1 (ℓ settled sludge)/(kg COD applied) or 0.14 (kg dry solids)/(kg COD applied) at an HRT of 42 h (Phase B), while this increased to 4.31 (ℓ settled sludge)/(kg COD applied) at a lower HRT of 22 h (Phase A).
- At high loading rates (Phase A), poor granulation and low microbial diversity was observed. Mass balance calculations indicated that the ABR operated as a solids accumulation device.
- At lower loading rates (Phase B), many granules were harvested and found to be much larger than the few observed in Phase A, had a better physical structure and greater microbial diversity. Approximately 60% of COD fed to the ABR was converted to methane in Phase B.
- It was concluded that the lower upflow velocities applied in Phase B allowed the establishment of stable methanogenic populations and resulted in overall better anaerobic digestion of the feed wastewater.
- These results suggest that the upflow velocity is the limiting factor that determines the organic and hydraulic loading rates that may be applied in a baffled reactor design. Upflow velocity appears to control the specific sludge accumulation rate, and thus, ultimately the required desludging interval for any particular system.
- It was further concluded that, since microbial respiration rates were limited by low pH values and low substrate concentrations, the critical upflow velocity is not a global value, but system specific and dependent on prevailing pH conditions determined by alkalinity concentration and organic strength of the wastewater to be treated.
- Thus selection pressure as defined by Hulshoff Pol *et al.* [1] is a function of organic loading rate, hydraulic loading rate, up-flow velocity and alkalinity, and all 4 factors should be considered when designing an anaerobic digester.

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Anaerobic digestion of domestic wastewater

Role of alkalinity in the rate and extent of digestion

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Anaerobic Digestion of domestic wastewater

- Anaerobic digestion
- Domestic wastewater

Particulates

\[ \text{H}_2 \]

Complex solubles

\[ \text{CO}_2 \text{ and H}_2\text{O} \]

Organic acids

Acetic acid

Methane

- Complex
  - Particulate inert
  - Soluble biodegradable

- Protein, carbohydrate, lipid and inert components
Factors affecting digester stability

- Digester stability depends on the development of a stable, active sludge
  - 3 main contributing factors
    - Microbial growth rate:
      - how fast is new sludge generated?
    - Sludge washout rate
      - How fast is sludge washed out?
    - Granulation rate
      - How do granules develop under operating conditions?

All 3 are interdependent

Depends on:
- Type and concentration of feed + inhibitory conditions.
  (e.g. pH, pO2, DO conc., chemical inhibitors)
- Particle settling characteristics, up-flow velocity

Growth of micro-organisms

- Anaerobic micro-organisms tend to be slow growing
- Changes in chemical conditions can disrupt sub-processes
  - Slow overall digestion
  - Interrupt sequence of digestion reactions (e.g. souring)

- Important factors
  - pH: optimal range 6.5<pH< 8.2
  - Chemical inhibitors: e.g. NH3, chlorinated hydrocarbons, NaCl. If concentration exceeds inhibition threshold, one or more anaerobic sub-processes may be inhibited.
Sludge washout rate

- In an up-flow system solids are washed out of the system if the settling velocity of the solid is less than the liquid flow upward velocity.

- Sludge washout rate depends on
  - Sludge particle size
  - Up-flow velocity
  - Solids density
  - Nature of flow (pulsing/steady)

- The rate at which solids accumulate or are depleted depends on
  - Rate of solids influx
  - Microbial growth on substrate (increases solids)
  - Rate of solids egress by entrainment

Growth of granules

- Complex many-layered structures
- Consist of
  - highly structured microbial consortia
  - extracellular polymeric substances (EPS)
  - Gas vesicles
  - Inorganic material (sometimes)
- 500µm – 10 mm
- Settle faster than dispersed sludge

- Granule formation favoured by high strength soluble substrates
- Often not reported in domestic wastewater applications
Selection Pressure

- The continuous selection of sludge particles on the basis of size, density and structural integrity by the continuous application of hydraulic shear forces from upflow through a granular bed*

  • Upflow results in the washout of small granules or granule debris


Role of alkalinity

- Alkalinity is related to the capacity to neutralise additional acid without experiencing a change in pH value
  - “a measure of the ability of a solution to neutralise acids to the equivalence point of carbonate or bicarbonate”

- Presence of significant concentrations of alkalinity assists in maintaining near-neutral pH values for anaerobic digestion

- Contributing ions $\rightarrow$ HCO$_3^-$; OH$^-$; PO$_4^{3-}$; NH$_3$ (and other conjugate bases of weak acid/base pairs)
Source of alkalinity

1. Influent alkalinity: present in influent wastewater → predominantly HCO$_3^-$

2. Metabolism generated alkalinity: generated in the process of anaerobic digestion, usually through the degradation of proteins by the release of NH$_3$:

$$R - CH - NH_2 - COOH + 2H_2O \rightarrow RCOOH + NH_3 + CO_2 + 2H_2$$

$$NH_3 + H_2O + CO_2 \rightarrow NH_4^+ + HCO_3^-$$

(also salts of organic acids and reduction of sulphate or sulphite)

Effect of alkalinity on microbial selection pressure (1)

- Alkalinity determines solution pH (and resistance to change in pH value)
- pH affects growth rate
- Growth rate affects balance between sludge accumulation and sludge depletion by washout
- Therefore alkalinity affects whether sludge (especially granular sludge) can grow effectively at the prevailing washout rate.
Effect of alkalinity on microbial selection pressure (2)

- Consider two scenarios
  
  (A) Moderate organic loading rate + insufficient alkalinity
  - pH < 6.5
  - slow growth rate
  - Moderate up-flow velocity
  - Difficult to retain active stable sludge

  (B) Moderate organic loading rate + sufficient alkalinity
  - 6.5 < pH < 8.2
  - Moderate growth rate
  - Moderate up-flow velocity
  - Stable sludge develops

Experimental Study

- 3 m³ pilot-scale reactor
- 8 compartments
- Domestic wastewater feed
- Operated under (relatively) controlled conditions at Kingsburgh WWTW
- HRT of 22h and 42h

Performance Indicators
- Physical-chemical properties
  - COD, pH, alkalinity, ammonia, TS, VFA
- Settled bed height in up-flow side of each compartment
Experimental study

<table>
<thead>
<tr>
<th></th>
<th>Phase A (high flow)</th>
<th>Phase B (low flow)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HRT [h]</td>
<td>22</td>
<td>42</td>
</tr>
<tr>
<td>Ave. upflow velocity [m/h]</td>
<td>0.55</td>
<td>0.27</td>
</tr>
<tr>
<td>Organic loading rate [kgCOD/m³.d]</td>
<td>0.74</td>
<td>0.40</td>
</tr>
<tr>
<td>Alkalinity [mg CaCO₃/ℓ]</td>
<td>240-246</td>
<td></td>
</tr>
</tbody>
</table>

Results (i): solids accumulation

<table>
<thead>
<tr>
<th></th>
<th>Phase A (High flow)</th>
<th>Phase B (Low flow)</th>
</tr>
</thead>
<tbody>
<tr>
<td>COD in mgCOD/ℓ</td>
<td>680 ± 25 (n=258)</td>
<td></td>
</tr>
<tr>
<td>COD out mgCOD/ℓ</td>
<td>212 ± 37 (n=57)</td>
<td>130 ± 29 (n=18)</td>
</tr>
<tr>
<td>Sludge accumulation rate m³/year</td>
<td>2.28 – 4.64</td>
<td>0.60 – 1.20</td>
</tr>
</tbody>
</table>

i.e. organic loading rate during A is < 2 x bigger than for B
BUT Sludge accumulation rate during A is > 2 x bigger than for B
Results (ii): Overall mass balance

- An overall mass balance calculation was performed for both phases to estimate methane production as follows:
  \[
  \text{COD}_{\text{CH}_4} = \text{COD}_{\text{in}} - \text{COD}_{\text{out}} - \text{COD}_{\text{sludge}}
  \]

<table>
<thead>
<tr>
<th></th>
<th>Phase A (high flow)</th>
<th>Phase B (low flow)</th>
</tr>
</thead>
<tbody>
<tr>
<td>COD removed</td>
<td>69%</td>
<td>81%</td>
</tr>
<tr>
<td>COD converted to CH₄</td>
<td>30%</td>
<td>60%</td>
</tr>
<tr>
<td>Estimated CH₄ production rate</td>
<td>250 kgCOD/year</td>
<td>260 kg COD/year</td>
</tr>
</tbody>
</table>

- Better overall COD removal at lower flow rate
- Higher COD conversion efficiency at lower flow rate
- Higher absolute CH₄ production rate at lower flow rate!!

Results (iii): Granule formation

- Granules from Phase A and Phase B were observed under a scanning electron microscope (SEM):

Phase A (high flow): small, brittle with little structural definition.

Phase B (low flow): larger, well-formed, with distinct layered structure.
Results (iv): pH and alkalinity

- pH and alkalinity profiles were obtained for compartments of the ABR.
  - Slight increase in alkalinity observed (metabolism generated alkalinity)
  - Alkalinity increase not sufficient to buffer production of acidity

![Phases A and B pH and Alkalinity Profiles](image)

Results (v): pH comparison

- pH profiles between Phase A and Phase B were similar
- pH profiles in Phase B were on average lower than in Phase A, indicating a greater extent of reaction (i.e. more influent COD had been converted in Phase B)

![Comparison of median pH profiles between Phase A (red) and Phase B (green)](image)
Discussion of experimental study (i)

• At higher flow rate, higher sludge accumulation rates observed
  – Due to poor digestion of particulate component of wastewater
  – Undigested solids accumulate
  – Active biomass does not establish due to low growth rates
  – Poor granulation and poor methane production rates observed

• At lower flow rates
  – A larger fraction of influent COD was converted to CH$_4$
  – Lower sludge accumulation rates observed
  – Active biomass accumulated and good granulation was observed

Discussion of experimental study (ii)

• Microbial selection pressure was determined by
  – Up-flow velocity (variable in this study)
  – Organic loading rate (variable) and substrate type (pseudo-constant)
  – Alkalinity (pseudo-constant)

• NOTE: literature indicates that stable digestion should occur at much higher upflow velocities, depending on the application e.g.
  – Lin and Yang (1991) : 0.7 m/h
  – Sasse (1998): 2 m/h
  – Hulshoff Pol et al. (2004): up to 60 m/h
  – This study: 0.27 m/h (stable) and 0.55 m/h (unstable)

• The cause of poor performance in this study was the low influent alkalinity (200 – 300 mgCaCO$_3$/ℓ)
  – Low alkalinity resulted in low pH (around 6.5 throughout the study)
  – Low pH caused low growth rates
  – Low growth rates resulted in poor granulation when upflow velocity exceeded ~ 0.3 m/h
Conclusion

• Selection pressure controls the development of a microbial community under particular operating conditions. It is a function of
  – Organic loading rate and substrate type
  – Up-flow velocity
  – Alkalinity, pH (and absence of other inhibitory factors)

• Low alkalinity can result in pH inhibition of growth processes

• Physical design of the up-flow reactor should be determined based on the required up-flow velocity for the given organic loading rate and alkalinity

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