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SCUM FORMATION AND CONSOLIDATION IN COVERED ANAEROBIC LAGOONS

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KEYWORDS

Anaerobic lagoons, scum formation, scum consolidation, compressibility, permeability

ABSTRACT

Scum builds up in covered anerobic lagoons that reduces hydraulic retention time, inhibits biogas capture, and damages lagoon covers. We demonstrate that the majority of this biomass sinks when degassed, indicating it mostly consists of undigested sludge floated by biogas. Thus, scum accumulation is inevitable and is not prevented by source control of fats, oils and floating debris; scum must be periodically and mechanically removed. We develop a theory of scum consolidation and desaturation driven by buoyancy and evaporation, and measure scum permeability and compressibility, to predict scum behaviour. Continued scum accumulation leads to densification and eventually crusting. The recommended scum management technique involves frequent agitation at low accumulation to liberate biogas, sinking biomass to digest it.

INTRODUCTION

Anaerobic digestion is an important wastewater treatment process for a sustainable future since the biogas can be used to generate electricity Shen et al., 2015; Cruddas et al., 2021. In covered anaerobic lagoons, dense solids in the influent settle in the lagoon, digest, and the biogas is captured by the cover. Unlike anaerobic digestors, lagoons are usually not mechanically mixed or heated, thus they generally have low operating and maintenance costs Paul, 1996; Türker et al., 2009. However, lagoons are not stagnant, despite the absence of mechanical mixing. There are complex hydrodynamics caused by inflow and outflow pipes, solid-liquid separation caused by differences in phase density, and biological activity Papadopoulos et al., 2003; Cruddas et al., 2021. Scum can form at the liquid surface that will reduce the effective volume and hydraulic retention time of the lagoon. Thick scum limits biogas transport and thereby reduces electricity generation. Scum adheres to and damages covers, which prevents biogas capture until covers are fixed or replaced Paul, 1998.

Scum layers can form through multiple mechanisms: 1) buoyant influent solids such as fats and oils naturally float; 2) convection currents can push solids of any density to edges and corners, which then adhere to covers; and 3) solids denser than water settle but can subsequently attach to biogas bubbles generated by digestion Paul, 1996. These attached solids are transported to the surface, forming a net positive buoyancy scum comprised of a strong matrix of negatively buoyant solids and biogas. It is not clear which of the three formation mechanisms dominate nor how scum gets thicker with time.

The aim of this paper is to inform scum management practices by better understanding scum formation mechanisms and scum layer mechanical behaviour. To achieve this, we undertake physical characterisation of scum samples from full-scale lagoons, including measurement of solids density, solids concentration, compressibility, and permeability Stickland et al., 2008. We develop a phenomenological model of scum layer consolidation and desaturation driven by buoyancy and evaporation based on Compressional Rheology Buscall and White, 1987; Stickland, 2015. Finally, we use the phenomenological model and the measured scum properties to predict the solids concentration profile of scum layers as a function of accumulated scum and evaporation rate.

HIGHLIGHTS

- Lagoon scum automatically forms due to sludge floated by biogas
- Accumulation and evaporative flux combine to consolidate and desaturate scum
- Scum has increasing strength and decreasing permeability at higher concentrations

- Active scum management requires frequent disruption to release gas and sink solids

METHODOLOGY

Scum was sampled from covered anaerobic lagoons at Melbourne Water's Western Treatment Plant (WTP) in Werribee, Victoria, and Barwon Water's Colac Water Reclamation Plant (CWRP). The solids concentration of these samples was measured by mass loss upon drying to equilibrium and solids density using a gravity cup Mercer et al., 2021. Filtration and sedimentation tests were performed to measure permeability and compressibility Stickland et al., 2008; Skinner et al., 2015. A model of scum consolidation and desaturation was developed based on steady-state compressional rheology Buscall and White, 1987.

RESULTS

Scum Consistency and Density

The scum samples were thick suspensions relative to sludge Skinner et al., 2015; the WTP scum (see Fig. 1A) was 20.6 wt% solids and the CWRP scum 14.6 wt%. Upon dilution and stirring, any gas in the samples was released. The WTP scum separated into floating solids such as hairs, seeds, and plastic beads, and settling sludge-like material (see Fig. 1B) with a solids density of 1283 kg/m^3. All of the CWRP scum settled upon dispersion (1022 kg/m^3). The absence of larger, floating solids in the CWRP scum was due to screening of the influent, which was not performed at WTP.

Scum Dewaterability

The dewaterability of the degassed scum samples was measured using filtration and batch sedimentation tests Stickland et al., 2008; Skinner et al., 2015 in terms of the compressive yield stress, $p_y(\phi)$, and the hindered settling function, $R(\phi)$ (see Fig. 2). $p_y(\phi)$ indicates the equilibrium strength of the solids network in compression and is zero below the gel point, ϕ_g, which is around 0.05 v/v for the scum, and increases with solids concentration. Scum dewaters to high solids concentrations (0.5 to 0.6 v/v) at compressive pressures of 300 kPa. $R(\phi)$ characterises the interphase drag, which indicates how fast solid and liquid separates; scum has very poor permeability at high concentrations. These dewaterability traits are all typical of wastewater sludges Skinner et al., 2015.

Crusty Scum Model

A 1-D steady-state model of scum was developed to predict its consolidation and desaturation. When the combined density of the solids and gas phases in scum are less than the fluid phase (that is, the phase density $\Delta\rho$ is negative), there is an upward buoyancy force. Also, evaporation from the scum surface causes a liquid flux q through the scum to supply fluid to the surface, which causes an upward hydrodynamic drag. These upward forces are resisted by the pore capillary pressure at the scum surface, which therefore causes consolidation of the network.

The steady-state volume fraction $\phi(z)$ for a saturated compressible porous network can be determined by

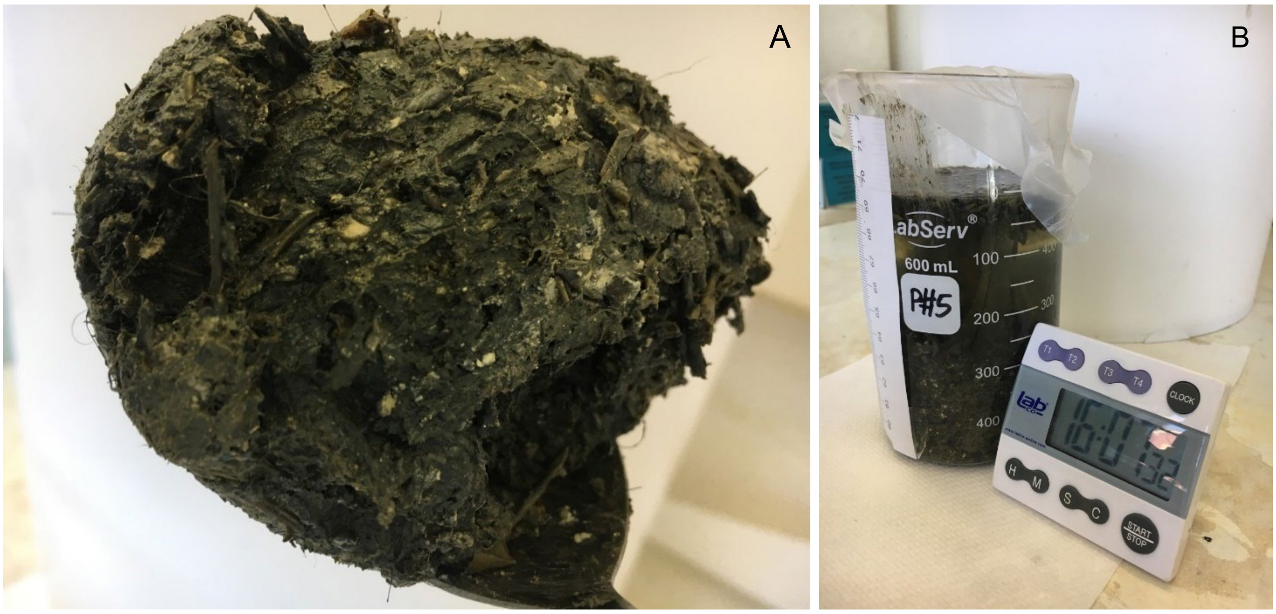

Figure 1(A): Scum sample from Western Treatment Plant. (B) Stirred scum sample allowed gas to be released and the solids to separate into settling (sludge-like) and floating (seeds, hairs, plastics, etc) fractions.

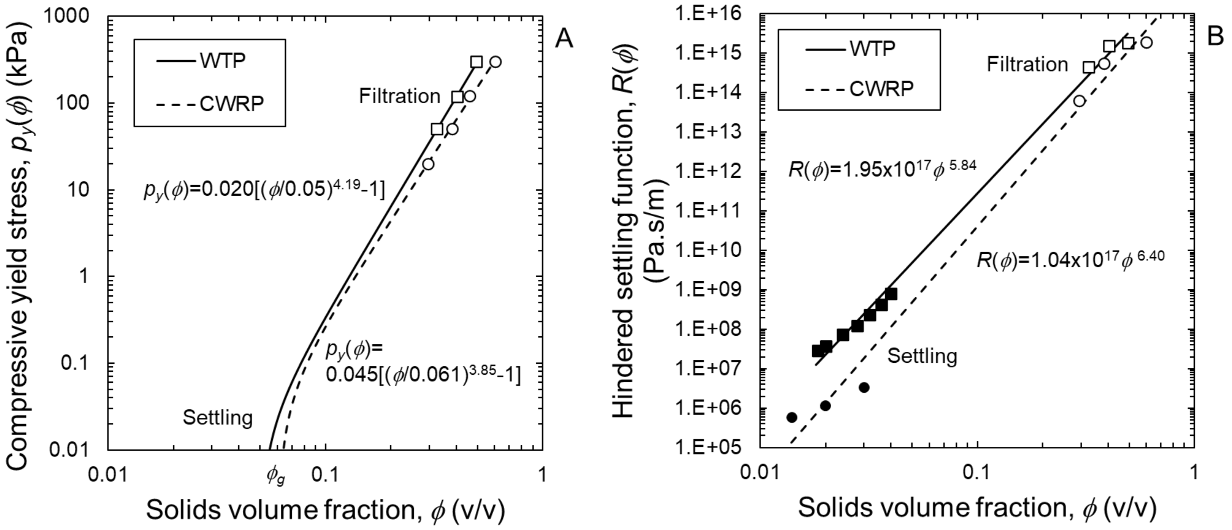

Figure 2: (A) Compressive yield stress and (B) hindered settling functions of scum samples from Western Treatment Plant (WTP) and Colac Water Reclamation Plant (CWRP) measured by filtration and settling tests

balancing the upward buoyancy and evaporative flux with the scum compressive yield stress. The steady-state gradient of the volume fraction is given by Eq. (1) Buscall and White, 1987:

$$\frac{d\phi}{dz} = \frac{1}{D(\phi)}[q\phi - f(\phi)], \qquad (1)$$

where $D(\phi) \equiv \frac{(1-\phi)^2}{R(\phi)}\frac{dp_y(\phi)}{d\phi}$ is the solids diffusivity, q is the evaporative bulk flux and $f(\phi) \equiv \frac{(1-\phi)^2}{R(\phi)}\Delta\rho g\phi$ is the buoyancy-driven creaming flux. Eq. (1) is numerically integrated from $\phi(h_\infty) = \phi_g$ at the bottom of the scum to $\phi(0) = \phi_h$ at the top, with h_∞ and ϕ_h given by the conservation of volume, M (Eq. (2)):

$$M = \int_{h_\infty}^{0}\phi(z)dz = \int_{\phi_g}^{\phi_h} z(\phi)d\phi. \qquad (2)$$

At a specific breakthrough pressure or critical volume fraction ϕ^*, the scum surface will desaturate rather than consolidate since the network strength exceeds the maximum capillary pressure that the pores can hold Brown et al., 2002; Stickland et al., 2014. Thus, when $\phi_h > \phi^*$, the scum desaturates and forms a crust. Once desaturation occurs, the local saturation varies according to Richards' equation Richards, 1931.

Fig. 3 shows the predictions of scum consolidation using the measured WTP scum properties with varying evaporation rate and gas content (indicated by changing $\Delta\rho$). Increasing accumulation adds more buoyany and therefore increases scum concentration. Evaporation becomes more difficult as the scum layer becomes thicker, denser, and more impermeable. Eventually, hydrodynamic resistance increases to a point where the given evaporation rate cannot be achieved and the capillary pressure diverges. For $\phi > \phi^*$, the scum desaturates and crust forms.

CONCLUSIONS

Our experiments show that degassing anaerobic lagoon scum samples causes most of the scum to settle like a sludge, therefore the predominant scum formation mechanism is via sludge flotation. This implies that scum is automatically produced during digestion along with biogas. Fats, oils, greases and floating debris contribute to scum, but scum will still form without buoyant solids in the influent. Thus source conrtol and/or influent screening will not prevent scum formation.

The crusty scum model predicts that, as scum accumulates, the total buoyancy force increases, causing consolidation and decreasing permeability. Evaporation can become rate-limiting. Enough accumulation will cause desaturation at the scum surface, which is likely to adhere to covers and be difficult to remove. The model allows lagoon operators to understand the consistency of scum as it develops.

The implication for operators of covered anaerobic lagoons is that scum must be actively managed to prevent build up problems. One method could be periodic degassing using mechanical or hydraulic scouring from underneath to return the scum biomass to the active sludge for digestion.

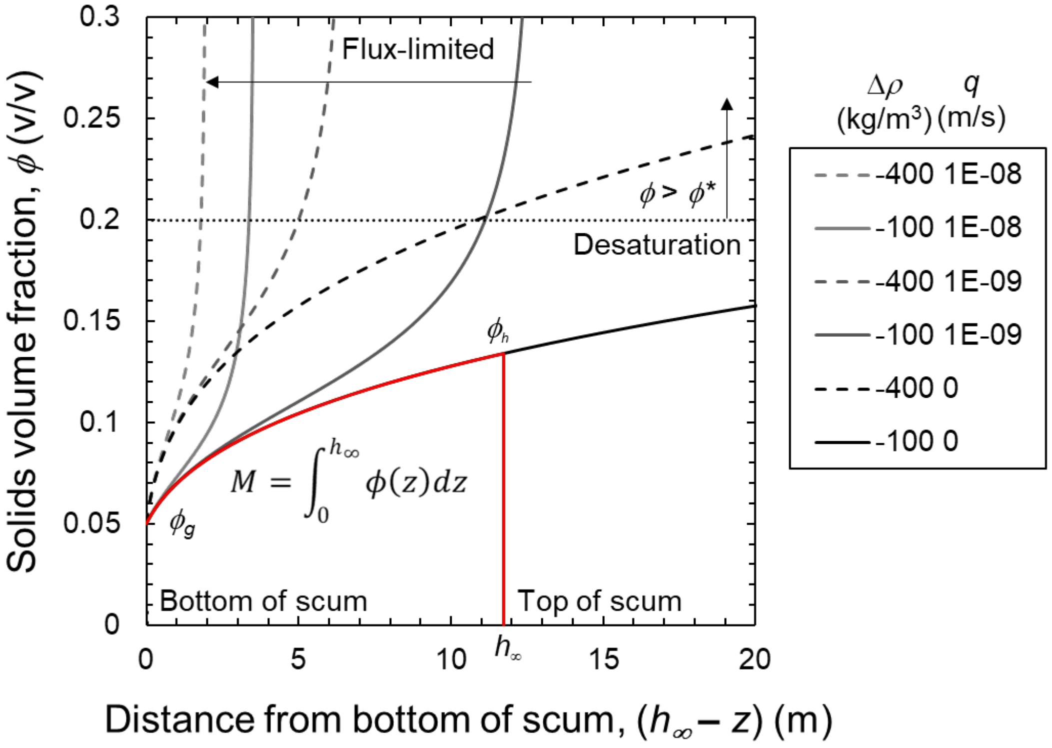

Figure 3: Crusty scum model predictions of steady-state volume fraction distribution using WTP scum properties for varying density differences $\Delta\rho$ and evaporation fluxes q. The bottom of the scum is at the gel point, $\phi(z = h_\infty) = \phi_g$, and the top of the scum is $\phi(z = 0) = \phi_h$, which is given by the conservation of volume for a known accumulation M. Varying $\Delta\rho$ represents increasing biogas fraction; -100 kg/m^3 is 30:70 biogas:solids and -400 kg/m^3 is 53:47 biogas:solids. When q = 0, buoyancy drives consolidation. As M increases and at high q, the volume fraction diverges since the bed is highly impermeable and consolidation becomes flux limited. At high volume fractions, $\phi > \phi^*$, the compressive yield stress exceeds the capillary pressure, and the porous network desaturates.

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