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The filtration characteristics of anaerobic digester effluents employing cross flow ceramic membrane microfiltration for nutrient recovery

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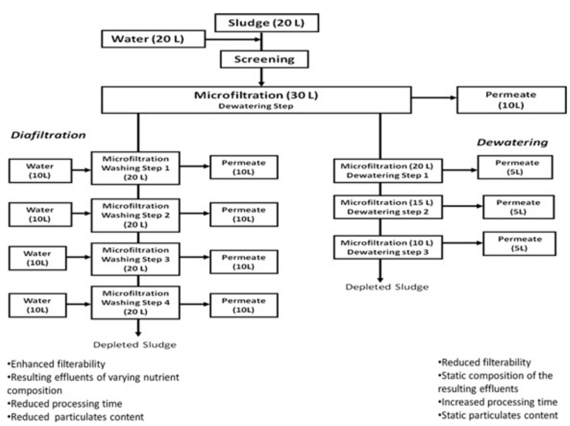
HIGHLIGHTS

- Digested effluent filterability was tested by a ceramic MF system of processing volume 140 L/m^2 h.
- Pretreatment scheme reduced TS by 20.75% and 48.58% coarse particles (PDS 27.17 to 13.97 μm).
- Diafiltration and dewatering schemes were tested for fluid processability at TMP 15 psi.
- A compressible permeable cake layer was formed allowing continuous operation in DF.
- Enhanced filterability of fluids and varying concentrations in nutrients are found using DF

GRAPHICAL ABSTRACT



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ABSTRACT

In the present study, a monolithic alumina coated microfiltration ceramic membrane was used for solid particulate removal and nutrient recovery from anaerobic digester complex effluent streams. The aim was to test the effect of the cake layer developed by the solids, on the surface of the membrane channels, to the filterability of these materials. The solid content ranged between 2.6 g/L to 15.1 g/L. During practical application, two processing techniques targeting the enhanced recovery of the materials of interest including ammonia, phosphate, calcium bicarbonate and volatile fatty acids, namely dewatering and diafiltration, were used. These had an immediate effect on the solid content (PDS 13 μm to 3.97 μm) enhancing the filterability of the effluents. Their processability was evaluated in terms of flux, cross flow velocity, membrane resistance and cake resistance. An important finding of this study is the nonalignment of the flux rates to the cake resistance, explained by the formation of a compressible, permeable cake layer that allowed the continuous operation of the system, under constant low pressure conditions (TMP 15 psi). Permeate flux remained constant to 120 L/m^2 h when applying diafiltration, while when dewatering process is used the permeate flux remained constant at 115.4 L/m^2 h.

1. Introduction

A key operation in the sustainable use of materials is the removal and recycling of nutrients and energy from the anaerobic digesters [1–3].

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In the quest for substitute fossil fuel alternatives sources, the development of anaerobic digesters for biogas production used for combined head and power (CHP) has been proposed [4,5,44]. Being relatively easy to be constructed, enhancing local and national economies by supporting small and medium sized companies [6] and relying on a well known and widely investigated process of anaerobic fermentation [7], the use of anaerobic digesters has seen rapid expansion throughout Western Europe and the United States [8]. In the Western economies the production via anaerobic digestion of biogas for power generation represents the 1.2% of the annual production of electricity and nearly 10% of renewable energy, with an installed power close to 1500 MW [9].

However, as the raw materials used as substrate during the digestion are mainly animal, crop and food wastes, the waste effluents that are generated from the process can be potentially hazardous to human health and environment having high concentration of freely available nutrients. The current treatment predominantly involves land spreading which can potentially cause eutrophication and land toxicity due to excessive phosphate and ammonia application [10]. There are also human health concerns due to land related pathogenicity [11,12] contained in the raw materials.

These concerns have highlighted the problems of sludge disposal. At the same time the value of nutrients is increasing due to high manufacturing costs or reduced availability such that recovery is of vital importance and is becoming economically viable [13]. For example, ammonia and phosphate are becoming more costly, since ammonia synthesis has an inherently large carbon footprint and consequently is heavily dependent on fossil fuel prices, and phosphate production is already thought to have peaked, hence the need for an effective treatment method has emerged [14]. Mechanical separation and recovery of nutrients from waste, using membrane processes, has been proposed and applied to many simple, well defined waste systems, e.g. recovery of cell metabolites and water [15].

Microfiltration pore size ranging from 0.1 μm to 1 μm allows smaller particles such as aqueous salts, small macromolecules, carbohydrates, proteins, metal ions and other inorganic and organic molecules to pass through formulating a sterile permeate effluent [16]. With larger particles removed these permeates can be further processed to recover useful nutrients as well as metal ions, or even used as substrates for microbial growth, which is an emerging option in the constantly evolving field of biotechnology [17]. Several beneficial features lay in membrane processing, [18–20] including reuse and more economical disposal of waste [21,22], formulation of sterile streams [23], low pressure operation, and ease of in-situ separation in addition to simple scale-up using commercial modules. These processes have shown treatment feasibility for several types of aqueous waste streams [24]. Research has been focused on treatment of municipal, domestic and sewage sludge [10,11,19,20,23,24].

The main problem that develops is membrane fouling which needs to be avoided and may require frequent cleaning of the membrane to manage the process effectively [21]. Several researchers [25,26] have investigated the filterability of sludge types in relation to cake formation due to solid deposition on the membrane surface [27,28]. Cake formation results in increased membrane resistance and decreased flux i.e. limited cost effective recovery of the materials of interest through decreased membrane productivity and increased energy consumption [29]. These processes involve the use of synthetic membranes such as polysulfone or polypropylene or inorganic, ceramic membranes [30]. Ceramic membranes have been widely applied in the industry, although due to their high cost compared to their polymeric counterparts, their application has been limited in the field of food, beverage and pharmaceutical industry [47,48]. However, their exceptional advantages, chemical and thermal stability as well as robust structural stability have attracted interest to their potential use in the treatment of waste streams [49]. Ceramic filters, either monolithic or tubular have been proven effective for the separation of various colloidal effluents of micron and sub-micron suspended particles [50]. Monolithic membranes have numerous parallel channels arranged in the axial direction, with the inner surface of the channels acting as filters offering a large membrane area suitable for processing significant amounts of effluent [38,41,51]. Ceramic filters are fabricated using alumina, zirconia or zeolite, materials that withstand extreme pH, pressure conditions and high flux rates [47].

These characteristics facilitate effective cleaning with acidic or alkali solutions, indicating ceramic membranes as ideal candidates for processing complex effluent streams of sludge nature [49]. Ceramic membrane configuration, does allow the deposition of particles in the inner side of the channels, forming a cake, which may hinder the permeate flux. Moreover, experimental investigation of waste stream has been limited to small scale [31,32], where the fluid and membrane arrangements offer limited information on the applicability of these methods and processing techniques on the industrial scale.

Therefore, this work reports the filtration of spent agricultural sludge through a ceramic membrane filter in a pilot scale arrangement. Its filterability has been evaluated in terms of flux, membrane resistance and cake resistance, using various operating conditions. Attempts have been made to correlate the solid contents and characteristics with the filterability of sludge using different treatment schemes. These correlations, when applied with the universal model for flux prediction, can be used to predict the filtration behavior of these complex systems, as well as to identify the necessary processing time needed to extract the necessary amounts of nutrients.

2. Materials and methods

2.1. Materials

Waste effluent (agricultural wastewater derived from agricultural digested sludge namely mixed waste of cattle slurry, vegetable waste and silage) stream samples taken off the output line of a sedimentation tank (before any treatment) were collected from Farm Renewable Environmental Energy Limited (Fre), Wrexham, United Kingdom. These were samples were taken of the output line of the anaerobic digester used for manure production before passing through the automatic coarse particle separator (>5 mm) and collected in 25 L capacity plastic jerry cans.

2.2. Experimental

2.2.1. Effluents pre-treatment schemes

The effluents were considered to be rich in solids, mostly comprised of large particles i.e. straw, stones. These had to be removed for the successful filtration of the effluents. A pre-treatment scheme was developed to address this problem, combining dilution with tap water (50% v/v), thorough mixing for 1 h using a rod, twenty-four hour sedimentation in a settling tank and treatment of the supernatant with a series of coarse filters varying in pore size between 1.045 mm to 0.5 mm [58].

2.2.2. Filtration unit design

The waste was processed through a cross-flow microfiltration unit (Fig. 1). The unit consisted of a 100 L stainless steel vessel linked via 5 m of 1 in. stainless steel piping arranged in two fluid loops each driven by a centrifugal pump, Kennet -12-2 (Stuart Turner, UK). Waste was passed from the tank into the first pump loop which pressurized the system against a diaphragm valve (Axium Process, Hendy, Wales, UK) on the return side, which could be adjusted to control the pressure. Within this loop a second pump circuit feeding the membrane (Membralox ceramic (α-Al_2O_3) monolith microfiltration (pore size 0.2 μm), able to withstand a pH range between 0 and 14, fitted in stainless steel, commercially available by Pall (Portsmouth, UK)) and water cooled heat exchanger (Axium Process, Hendy, Wales, UK) enabled high flow rate around the loop. There was very little pressure dropping in this loop and as such high fluid velocity over the membrane surface was achieved, which could be kept constant over a range of pressures. The membrane comprised of 19 channels, of 3.70 mm diameter each and length of 1016 mm. The effective membrane area was determined