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Osmotic pressure and substrate resistance during the concentration of manure nutrients by reverse osmosis membranes

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ABSTRACT

The objective of the membrane technology presented here is the production of nitrogen concentrates from pretreated swine manure. This paper reports on the effect of osmotic pressure and substrate resistance on transmembrane flux during the concentration of prefiltered swine (PFS) manure by reverse osmosis (RO) membranes. The PFS manure at various concentration levels was filtered by four highly selective polyamide RO membranes with maximum allowable pressures ranging from 41 to 83 bar. The osmotic pressure created by the PFS manure on the RO membranes fitted a second-order equation with respect to manure conductivity or total ammonia-nitrogen (TAN), indicating that the rate of increase in osmotic pressure accelerated as manure was being concentrated. Average osmotic pressure increased by a factor of 6.8, from 5.4 to 36.6 bar, as TAN was increased 5.6 times, from 1.6 g to 9.2 g/l. Substrate-related resistance, which has been attributed to specific membrane–solute interactions even in the absence of flow, tended to increase as PFS manure concentration increased. However, reduction in transmembrane flux during manure concentration was mainly due to increase in osmotic pressure. If the objective of the technology is to concentrate manure in small volumes with high nitrogen concentrations, RO systems have to be equipped with membranes that are able to sustain high applied pressures, because the decrease in flow due to increased osmotic pressure along membrane elements will be substantial.

1. Introduction

In the past century, human activities have doubled the rate of nitrogen entering the N cycle, affecting ecosystems around the world [1]. Nitrogen fertilizer production, which is an important source of greenhouse gas emissions [2], accounts for over half the new available nitrogen. Steinfeld et al. [3] estimated that between 20% and 25% of mineral N fertilizers are used for livestock feed production. Most of this nitrogen is still available in the manure, because animals have a low nitrogen assimilation efficiency of about 10% globally and 20% for pigs [4].

It is imperative to reuse the excreted N, but many large swine operations do not possess the required cultivated land base to do so. Additionally, the transport of raw manure to feed-producing farms is not always profitable because manure contains between 90% and 99% of water and is basically a highly diluted fertilizer. Manure is also an unbalanced N–P–K fertilizer and application rates are increasingly limited by the maximum phosphorous load allowed on cultivated fields. Consequently, feed producers are still heavily relying on chemical nitrogen fertilizers, although regionally produced manure could supply most of the plant N requirements [5].

One solution consists in separating and concentrating manure nutrients in small volumes that could be economically transported to other farms. In recent years, physico-chemical technologies have been developed to concentrate up to 85% of the phosphorus in a solid phase representing between 10% and 30% of the raw manure [6]. The liquid fraction generated by some of these separators could be processed by reverse osmosis (RO) to produce nitrogen concentrates, the by-product being relatively clean water that could be used to wash barns or irrigate nearby cultures.

Short-term experiments with membrane systems have been reported in the literature, but there is little information on long-term performance and optimum operating parameters of the technology with respect to initial manure characteristics and targeted volumetric concentration [7]. The effects of osmotic pressure, substrate-, pressure- and time-related fouling, temperature and concentration polarization have not been quantified. Manure has a high salt content, including bicarbonates, volatile fatty acids, ammonia and potassium, that can exert a significant osmotic pressure on RO membranes at high recovery rates. A 62% decrease in flux was observed as permeate recovery rate was increased from 0% to 53% during the filtration of a wastewater containing 8.7 g/l of ammonia [8]. The decrease in flow was essentially attributed

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Table 1
Characteristics of the prefiltered swine (PFS) manures fed to the four RO membranes installed on the laboratory scale pilot.

Parameters	PFS manure						
	1	2	3	4	5	6	7
EC (mS)	14.3	23.8	33.4	41.3	51.6	54.2	61.3
DM (g/l)	4.99	8.86	16.46	27.70	31.01	33.76	41.13
DM vol. (g/l)	1.89	3.80	7.63	14.88	13.68	16.92	21.18
SS (mg/l)	503	1374	2550	4821	4050	3895	4840
VSS (mg/l)	388	1055	2070	3561	2945	2452	2930
TAN (mg/l)	1646	2982	4393	5734	7254	8174	9169
TKN (mg/l)	1669	3155	4929	6433	7957	8543	10317
K (mg/l)	1000	2004	2670	4300	5734	6477	7181
P (mg/l)	83	195	242	395	394	738	979
pH	8.23	7.98	7.98	8.43	8.61	8.41	8.42
Alk. ($gCaCO_3$/l)	5.00	11.10	16.25	21.83	27.38	30.00	33.50
VFA (g/l)	2.91	2.07	16.14	23.75	26.76	29.18	29.82

EC: electrical conductivity; DM: dry matter; DM vol: volatile DM; SS: suspended solids; VSS: volatile SS; TAN: total ammonia-nitrogen; TKN: total Kjeldahl nitrogen; K: potassium; P: phosphorous; Alk.: alkalinity; VFA: volatile fatty acid.

to increased osmotic pressure. However, reports on manure concentration by RO membranes do not generally isolate the effect of increased temperature, osmotic pressure, and fouling resistance on flux [9–11].

The resistance-in-series model provides a simple equation to describe transmembrane flux through membranes [12]:

$$J_s = \frac{\Delta P_t - \Delta\pi}{\mu(R_m + R_s + R_f)} \tag{1}$$

where J_s is transmembrane flux (m/s), ΔP_t is applied pressure (Pa), $\Delta\pi$ is osmotic pressure, μ is viscosity of the permeate (Pa-sec), R_m is the intrinsic membrane resistance (or resistance to pure water passage through the membrane), R_s is the resistance associated with the substrate being processed (m^{-1}), and R_f represents the resistance due to membrane fouling (m^{-1}).

The substrate-associated resistance (R_s) has been attributed to specific membrane–solute interactions, such as macromolecule adsorbtion on the membrane surface, even in the absence of flow [13]. It reduces flow from the outset of the filtration process. Chiang and Cheryan [14] found that the value of R_s for ultrafiltration membranes filtering skim milk was a constant over a range of crossflow velocities (0.34–1.11 m/s), temperatures (40–60 °C), and protein concentrations (3.1–11.5%). Nikolova and Islam [13], on the other hand, observed that the value of R_s was proportional to dextran concentrations between 3 and 50 kg/m^3. For both studies, the R_s values were of the same order of magnitude as the membrane intrinsic resistance R_m [15]. With highly charged wastewater, such as pretreated manure, however, the substrate-related resistance could significantly affect flux through the membrane.

The objective of this experiment was to quantify osmotic pressure and substrate-related resistance during the concentration of pretreated swine manure by RO membranes. This information is essential to design full-scale systems for farm application at the highest possible permeate recovery rate. Flux calculated using parameters estimated with a laboratory scale pilot was also compared to actual fluxes measured during the concentration of pretreated manure with a spiral-wound RO element installed on a semi-commercial scale pilot.

2. Materials and methods

2.1. Manure

The raw manure used with the laboratory scale membrane pilot was collected from the transfer storage tanks on a typical farrow-to-finish swine operation in Québec, Canada. The raw manure contained 47.8 g/l of dry matter (DM). It was filtered under vacuum as described in Masse et al. [16], producing a liquid fraction corresponding to the prefiltered swine (PFS) manure #3 in Table 1. The liquid fraction was concentrated with RO membranes or diluted with water to simulate manure at various stages of the concentration process. A total of 7 PFS manures with conductivities ranging from 14.3 to 61.3 mS were thus produced (Table 1).

The liquid fraction from an in-barn separation system was used with the semi-commercial scale (SCS) membrane pilot. The separation technology consists of a perforated conveyor belt placed under the pigs in a growing-finishing barn, as described in Dufour et al. [17]. The liquid fraction contains mostly urine mixed with

Table 2
Characteristics of the two pretreated manures concentrated with the spiral-wound RO3 membrane, as well as final concentrates and average permeates.

Parameters	LF1 – concentrated in 27% of initial volume			LF2 – concentrated in 30% of initial volume		
	Feed	Concentrate	Permeate	Feed	Concentrate	Permeate
EC (mS)	15.0	47.8	0.7	18.6	51.1	1.2
DM (mg/l)	5899	23074	91	8034	26357	119
DM vol. (mg/l)	2652	10248	12	3944	12590	NA
SS (mg/l)	1307	NA	NA	1330	4481	0
VSS (mg/l)	1097	NA	NA	1143	3617	0
TAN (mg/l)	1799	6433	222	2094	6723	191
K (mg/l)	1260	4942	16	1524	5218	15
P (mg/l)	52	185	0.12	72	202	0.12
pH	8.48	8.24	9.22	8.06	7.89	8.76
Alk ($mgCaCO_3$/l)	6608	24443	658	8074	25551	567
VFA (mg/l)	3575	14377	13	5266	16601	18

NA = not analysed.
EC: electrical conductivity; DM: dry matter; DM vol: volatile DM; SS: suspended solids; VSS: volatile SS; TAN: total ammonia-nitrogen; K: potassium; P: phosphorous; Alk.: alkalinity; VFA: volatile fatty acid.