ALTERNATIVE PHYSICAL TREATMENT METHOD FOR POULTRY PROCESSING WASTEWATER USING MEMBRANE FILTRATION

by

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(Under the Direction of Brian H. Kiepper)

ABSTRACT

Regulatory environmental permits governing wastewater disposal have become stricter for poultry processing plants that discharge effluent directly into the environment or pre-treat their wastewater stream prior to discharge to a municipal sewer systems. Therefore, more effective means of on-site wastewater treatment is a constant demand. The viability of membrane filtration as an on-site treatment method for pre- and post-DAF (dissolved air flotation) poultry processing wastewater (PPW) was investigated. A performance index (Pm_i) was used to indicate which membrane was the most effective and suitable for the membrane filtration of pre-and post-DAF PPW. For the membranes tested, the 0.3µm PVDF membrane was determined to be the most effective in treating pre-DAF PPW by producing a 115 $Lm^{-2}h^{-1}$ permeate flux, while the 100,000 MWCO Ultrafilic membrane was determined to be the most effective in treating post-DAF PPW by producing a 224 $Lm^{-2}h^{-1}$ permeate flux. COD, TS and TSS reductions are evaluated and reported.

INDEX WORDS: Poultry processing, wastewater treatment, membrane filtration, permeate flux, COD, TS, TSS

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DEDICATION

To my family and friends, thank you for the love and support.

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CHAPTER 1

INTRODUCTION

U.S. poultry processing plants are constantly faced with challenges resulting from the generation of high-strength wastewater and slaughter byproduct recovery and handling (APHA, 2005; Kiepper et al., 2008). Due to constant environmental pressures the poultry industry is relentlessly searching for better wastewater treatment practices. Since the inception of the Clean Water Act in 1972, regulations governing wastewater disposal have increased and become stricter on industrial and domestic wastewater treatment plants that discharge effluent directly into the environment (i.e., direct dischargers) (Del Nery et al., 2007; Kiepper et al., 2001; USEPA, 2002). Alternatively, poultry processing plants that discharge their effluent to local sewage systems (i.e., indirect dischargers) often must pay substantial surcharges fees to local municipalities to cover costs associated with treatment of high-strength wastewater discharges. Therefore the need for alternative, more effective means of wastewater treatment is a constant challenge for U.S. poultry processors (Avula et al., 2009).

Currently, more than 80% of poultry processors use a combination of mechanical screens followed by dissolved air flotation (DAF) to treat their wastewater on-site (Kiepper, 2003; Lo et al., 2005). Although DAF is effective, the aggressive aeration of the fine poultry processing wastewater particulates causes excessive oxidative damage and bacterial degradation of fat and protein components of the recovered byproduct (Del Nery et al., 2007; Park et al., 2001; Viitasaari et al., 1995). Also, various chemicals (e.g., metal salts, cationic and anionic polymers) are used in combination with the physical DAF process which improves treatment, but further adulterates and greatly reduces the value of the recovered DAF skimmings as a nutrient source in rendered animal byproduct feed ingredients. Thus, utilization and disposal of DAF skimmings is a major expense and inconvenience to the poultry industry (Kiepper, 2003).

There is great potential in exploring advanced physical separation systems (APSS) (e.g., microscreening and membrane filtration) on both pre- and post-DAF poultry processing wastewater (PPW) (Avula et al., 2009). The benefits of improved pre-DAF PPW treatment include a substantial increase in the volume of unadulterated byproduct (i.e., offal) recovered for rendering while reducing a corresponding volume of lower value DAF skimmings, substantial chemical cost savings, and a potential reduction in energy consumption. The benefits of improved post-DAF PPW treatment include reduced cost of operation of biological treatment systems and sludge volume production in direct discharge systems, and the potential to significantly reduce surcharge fees paid by indirect dischargers.

To examine the potential for use of APSS in pre- and post-DAF PPW treatment on-site at poultry processing plants, two membrane filtration experiments were completed. The first experiment (i.e., Chapter 3) involved the use of membrane filtration in the treatment of pre-DAF PPW as a potential enhancement or replacement for existing DAF technology. Flat sheet membranes within the microfiltration (i.e., 0.1-10µm) and ultrafiltration (i.e., 0.01-0.1µm) ranges that use a semi-permeable surface under pressure to separate colloids and high molecular weight materials in solution were tested on pre-DAF PPW. The 3 membranes sizes/materials tested were 0.30µm Polyvinylidene fluoride (PVDF), 0.10µm Polysulfone (PS), and 100,000MWCO (molecular weight cut-off) Ultrafilic at two operating pressures (i.e., 50 psi and 80 psi) on pre-DAF PPW pre-sieved (i.e., microscreened) to 106µm. Effluent permeate flux ($Lm^{-2}h^{-1}$), and concentration (mg/L) of chemical oxygen demand (COD) and total solids (TS) were measured and analyzed.

The second experiment (i.e., Chapter 4) involved the use of membrane filtration in treating post-DAF PPW. Flat sheet membranes within the microfiltration and ultrafiltration ranges were tested on post-DAF PPW to measure the potential for surcharge fee reduction. A total of six membranes (i.e., 0.3µm PVDF, 0.1µm Polysulfone, 100,000MWCO PVDF, 100,000MWCO Ultrafilic, 30,000MWCO PVDF and 30,000MWCO Polysulfone) were tested at 50 psi on post-DAF PPW pre-sieved to 106µm. Effluent permeate flux ($Lm^{-2}h^{-1}$), and concentration (mg/L) of COD, TS and total suspended solid (TSS) were measured and analyzed.

The results of both experiments were enumerated and comparisons were made with the results found (i.e., Chapter 5). General limitations of membrane materials, membrane pore sizes and transmembrane pressures are identified.

CHAP TER 2

LITERATURE REVIEW

The term poultry refers to a group of avian species that are raised for the production of meat and eggs. Poultry includes chicken, turkey, geese, quail, pigeons, pheasants, and ostrich (Perry et al., 1999). However for purpose of this thesis, the term poultry is used synonymously with young chickens (i.e., broilers) as defined by the United States Department of Agriculture (USDA), which account for over 95% of the 9 billion poultry processed in the U.S. on an annual basis (USDA, 2010).

Poultry processing plants utilize relatively large volumes of potable water to clean both products and processing equipment. In the U.S., commercial broiler slaughter plants use 19 to 38 L (5 to 10 gal) of potable water per bird processed (Kiepper, 2003; Northcutt and Jones, 2004). The live weight of poultry plays a critical role in determining the amount portable water utilized in processing. For example large male turkeys can weigh 18 kg (40 lbs) and require potable water volumes in the range of 130 to 150 L (35 to 40 gal) per bird for processing (Avula et al., 2009).

One common problem facing the U.S. poultry industry is that increasing levels of the water use, due to increased production levels, that results in a corresponding increase in high-strength wastewater generation (APHA, 2005). Most of the water used in poultry processing is for scalding, defeathering, evisceration, washing of equipment and carcasses, and overall plant sanitation. Also, water is used by poultry processors as a transport medium for byproducts generated during processing (e.g., offal including feathers, heads, and viscera) (Northcutt and Jones, 2004; Thornton and O'Keefe, 2002; Veerkamp, 1999).

Since the inception of the Clean Water Act in 1972, environmental regulatory permits governing wastewater disposal have consistently become stricter on industrial wastewater treatment plants that discharge effluent directly into the environment or to local municipal sewage systems. Poultry processing plants are classified as either 'indirect' or 'direct' wastewater effluent dischargers. Indirect dischargers pre-treat their wastewater stream on-site prior to discharge to local municipal sewerage collection systems commonly known as publicly owned treatment works (POTWs). Indirect dischargers are subject to both regulatory permit limits as well as surcharge fees set by local environmental authorities to recover added costs associated with the treatment of high-strength wastewater. Direct dischargers must fully treat their wastewater stream prior to releasing the treated effluent straight into the environment under federal or state environmental regulatory permit.

Poultry Processing Wastewater (PPW)

Poultry processing wastewater (PPW) consists of spent potable water and the proteins, fats and carbohydrates generated from the meat, blood, skin and feathers removed from the bird during processing. PPW also contains grit and other inorganic particulates (Fonkwe et al., 2001). The term PPW is typically used to define the combine wastewater stream generated during poultry slaughter after all processing operations and following offal screening which removes large solids from the PPW stream (e.g, feathers, heads and viscera). Prior to discharge of PPW, poultry processors are required to remove the majority of the soluble and particulate organic and inorganic material in order to comply with environmental regulations. With an estimated 2 to 5% of total carcass proteins lost to the wastewater stream during processing, PPW contains predominantly (i.e., ~35%) protein, resulting in a high-strength effluent with a substantially higher biochemical oxygen demand (BOD) and chemical oxygen demand (COD) concentration (mg/L) than domestic wastewater (Zhang, 1997). Thus PPW requires intensive treatment before it can be discharged (Wesley, 1985).

Characteristics of Poultry Processing Wastewater

PPW consists of various constituents in the form of organics, particulates and inorganic nutrients. BOD and COD are the two most common analytical tests used to assess the organic 'strength' of PPW. The series of analytical tests used to establish the concentration of particulates in PPW include total solids (TS), total suspended solids (TSS), total volatile solids (TVS), total dissolved solids (TDS) and total fixed solids (TFS). Inorganic nutrients of concern such as nitrogen (N) and phosphorus (P) can be found in substantial quantities in PPW. Also, pathogens (e.g., bacteria) and colloidal particles (e.g., fats, oil and grease) are found in PPW (APHA, 2005). The following is a glossary of common PPW terms:

BOD (biochemical oxygen demand) – measures the amount of oxygen used by aerobic microorganisms to stabilize the biodegradable organic matter in a wastewater sample (Metcalf and Eddy Inc., 2003). The BOD test is also known as BOD_5 since the test is conducted over a period of 5 days (USEPA, 2002). BOD involves calculating the change in the concentration of dissolved oxygen (DO) in a wastewater sample incubated at 20^{o}C over a 5-day period (APHA, 2005). BOD is the traditional test used to track the organic concentration of pollutants though the wastewater treatment process prior to discharge into a receiving water body (USEPA, 1974).

COD (chemical oxygen demand) – measures the amount of oxygen required for oxidation of the organic matter in wastewater using a standard reagent (APHA, 2005). A measured sample with a known excess of potassium dichromate ($K_2Cr_2O_7$) is mixed after the addition of sulfuric acid (H_2SO_4) and silver sulfate (Ag_2SO_4). The organic matter is oxidized over a 2 hour heating period at 150^oC. Once samples are cooled, all samples, blanks and standards are measured against a reference solution (reagent blank) at a 620nm wavelength. COD is a useful control parameter for oxidation operations, and given a consistent waste stream, a stable empirical ratio can be established between COD and BOD. Thus COD can be an effective predictor of BOD. COD is used as a more accurate, cheaper and less time consuming means of determining the effectiveness of wastewater treatment (Nielsen, 1989).

Colloidal particles – are solids in a liquid that do not settle due to gravity (i.e., low specific gravity) and as a result causes them to float or suspend in wastewater (APHA, 2005). These immiscible particles blinds screens, clogs pipes and pumping systems. They can cause decrease in the efficiency of aerobic reactors by reducing oxygen transfer. Oils and greases (O&G) are examples of common PPW colloidal particles.

DO (dissolved oxygen) – is the concentration (mg/L) of oxygen in solution in water (APHA, 2005).

Nutrients - are elements required to support living organisms. Poultry processing plants can contribute significant loadings of nutrients of concern (e.g., nitrogen and phosphorus) into PPW. PPW typically contains organic nitrogen, phosphorus and dissolved ammonia gas (Contreras et al., 2000; CSUS, 1993; Metcalf and Eddy Inc., 2003; Welch and Lindell, 1992). Nutrients are important in aquatic biosystems, but excess amounts accelerate eutrophication and is detrimental to water quality. The presence of ammonia in PPW results from the breakdown of proteins and other nitrogenous compounds which can be toxic to aquatic life. About 2 to 5% of the total carcass protein can be found in PPW (Grant, 1980). Mead (1989) reported the bulk of solids in PPW to be nitrogen, which can be recovered and recycled for feed for farm animals and pets. Nitrate (NO_3) is another pollutant of concern in water and is formed as a result of oxidation of ammonia. In high levels in natural water bodies, nitrate brings about excess algal growth and accelerated eutrophication (Eremektar et al., 1999; Welch and Lindell, 1992). Along with the nutrient present in poultry tissues, other factors that increase the pollutant load of nutrients in PPW can be attributed to cleaning agents and disinfectants used in cleaning the equipment and birds, grit or soil particles from the birds and transportation equipment, undigested feeds from the carcasses, and ingredients used in further processing operations (Kiepper, 2009; Mead, 1989; Merka, 2001). Excess nitrate in water is toxic to both microorganisms and public health. Excess phosphorus in water also adversely affects quality (Eremektar et al., 1999).

<u>TFS (total fixed solids)</u> – measures the concentration (mg/L) of inorganic solids in a wastewater sample. TFS are the remaining solids in the form of ash following the combustion of organic solids in a TVS test (APHA, 2005). It can be calculated by subtracting the TVS from TS.

<u>TDS (total dissolved solids)</u> – is the concentration (mg/L) of soluble inorganic and organic matter that is in solution in a wastewater sample (APHA, 2005). TDS is

determined by measuring the solids remaining in the filtrate that passes through the glass fiber filter in the TSS test (USEPA, 1974).

TKN (total Kjeldahl nitrogen) – measures the concentration (mg/L) of organic nitrogen and ammonia combined in a wastewater sample through acid digestion and distillation (Merka, 1989).

TS (total solids) – measures the concentration (mg/L) of the total amount of inorganic and organic matter recovered after a wastewater sample has been evaporated to dryness (APHA, 2005). A measured volume of wastewater is poured in a pre-weighed crucible and dried to dryness at 105^{o}C to a constant weight over a period of 24 hours (APHA, 2005).

TSS (total suspended solids) – is the concentration (mg/L) of insoluble inorganic and organic matter that is suspended in a wastewater sample (APHA, 2005; Nielsen, 1989). TSS is determined by passing a measured volume of wastewater through a standard glass fiber filter (i.e., $< 2.0\mu m$) and drying the filter to a constant weight at 103 to105^{o}C (USEPA, 1974).

TVS (total volatile solids) – is the concentration (mg/L) of organic solids in a wastewater sample. A measured volume of wastewater is evaporated and the residue combusted at 550^{o}C (APHA, 2005). The loss in weight is equal to the organic solids which volatilized during combustion. It can be calculated by subtracting the total fixed solids (TFS) from the total solids (TS).

To be able to meet environmental regulatory permits, most of the organics, particulates and nutrients must be removed from PPW before discharge (Kiepper et al., 2001; Mead, 1989; Merka, 2001). From the early 1960s to late 1970s, researchers reported average BOD readings from US broiler processing plants ranging from 400 to 1300 mg/L (Camp and Willoughby, 1968; Carawan et al., 1974; Chen et al., 1976.; Glide, 1968; Lillard, 1978; Nemerow, 1969; Singh et al., 1973; Teletzke, 1961; USEPA, 1975; Whitehead, 1979; Woodard et al., 1972; Woodard et al., 1977). Hamza et al. (1978) reported an Egyptian poultry processing plant generating wastewater with a BOD concentration of 2341 mg/L. As poultry processing plant line speeds have increased, there have been corresponding increases in BOD and COD levels of PPW. Merka (1989) reported an average BOD and COD concentrations of PPW to be 2178 mg/L and 3772 mg/L, respectively from a broiler processing plant. Avula et al., (2009), Del Nery et al.(2007), Eremektar et al. (1999), Kiepper (2009), Lo et al. (2005), Merka (2001), Rusten et al. (1998) and Zhang (1997), all reported increasing BOD and COD concentrations in PPW in recent decades.

TS and TSS in PPW show similar increasing trends over the years. Camp and Willoughby (1968) reported average TS and TSS concentrations of 650 mg/L and 196 mg/L, respectively in PPW. USEPA (1975) reported average TS and TSS concentration ranges of 600 to 1000 mg/L and 200 to 700 mg/L, respectively in a broiler processing plant survey. Merka (1989) reported average TSS and TVS concentrations of 1446 mg/L and 1745 mg/L. Rusten et al. (1998) reported an average TSS concentration of 1360 mg/L for PPW. Kiepper et al. (2009) reported TS, TSS and TVS concentration ranges of 2000 to 2700 mg/L, 880 to 1250 mg/L, and 1600 to 2200 mg/L, respectively, in PPW. Yordanov (2010) reported an average TSS concentration range of 2280 to 2446 mg/L in PPW.

The concentration of O&G collidial partciles in PPW was reported by Rusten et al. in 1998 at an average O&G concentration of 970 mg/L. Yordanov (2010) reported an average O&G concentration range of 289 to 389 mg/L in PPW.

Nutrient concentration levels in PPW have documented by Eremektar et al. (1999) who reported average phosphorus concentrations of 48, 16 18 and 40 mg/L for four different samples of PPW. Rusten et al. (1998) reported an average phosphorus concentration range from 14.1 to 18.5 mg/L. Kiepper et al. (2009) reported TKN concentration range of 120 to 250 mg/L in PPW.

The increasing trend these constituents is a result of increase in production poultry over the years, thus a corresponding increase with load on wastewater.

Table 2.1. Summary of the various constituents of organics, inorganics, particulates and nutrients in poultry processing wastewater (PPW)

Discharge Characteristics	**Range of Concentration (mg/L)**	**Average Concentration (mg/L)**
BOD	200-2341	1271
COD	1300-3772	2536
TS	600-2700	1650
TSS	200-2446	1323
TVS	1600-2200	1900
TKN	120-250	185
O&G	100-970	535
Phosphorus	14-50	32

The composition of wastewater from the poultry varies from one plant to another depending on the type of systems, the methods of operations, treatments and the processing loads (Zhang, 1997).

Poultry Processing Wastewater Treatment

Most of the water used in poultry processing is utilized for scalding, evisceration, washing of equipment and birds, and overall plant sanitation (Northcutt and Jones, 2004; Thornton and O'Keefe, 2002). These wastewaters cannot be simply discharged into water bodies like rivers and lakes because of the high content of organic and inorganic matters, and microorganisms they contain (Mead, 1989). Various treatment procedures can be used, ranging from simple mechanical screening to advanced biological treatment systems, to treat PPW. PPW primary treatment involves the separation of offal (i.e., inedible poultry byproducts) from the wastewater stream through physical separation (e.g., mechanical screens) driven by force or gravity (Pankratz, 1995).

Secondary treatment consists of advanced physical, chemical and biological processes that remove finer particulates of the poultry processing byproducts contained in PPW. Although effective, secondary treatment changes and adulterates the byproducts recovered from the wastewater stream, thus reducing their value and uses (Pierson and Pavlostathis, 2000).

Physical Treatment of PPW

Primary treatment of PPW traditionally involves the use of mechanical screens to physically remove coarse solids (i.e., offal) from the wastewater stream. Depending on the type of processing wastewater and desired removal efficiencies, other methods of physical treatment are available and have been documented by researchers. Examples include using air stripping to remove volatile compounds, sedimentation and sand filtration (Torrens, 2001). Barrett (1977) and Chen et al. (2002) documented electrolysis and electroflocculation to be effective in removing fine suspended solid particles in piggery wastewater. Electro-coagulation has also proven to be an effective method for treatment of animal processing wastewater. Kobya et al. (2006) found electro-coagulation to be an effective method for the treatment of PPW. Kobya et al. found that by means of combined usage of iron and aluminum as anode materials at appropriate treatment conditions, high levels of COD and O&G could be removed from PPW.

Screening

In most poultry processing plants, physical screening is the typical primary treatment method utilized. Mechanical screen are the most energy efficient and least expensive form of primary treatment in reducing solids in PPW. Currently, primary treatment of PPW at U.S. poultry processing plants consists of physical screening in the Fine (1500 to 6000µm) and Very Fine (200 to 1499µm) ranges as defined by the Water Environment Federation (Kiepper, 2003). Screening recovers offal (i.e., feathers, viscera, meat particles) removing the large solid particulates that might hinder operation of downstream treatment processes (Arundel, 1995; Pankratz, 1995).

Screening is defined as the physical removal of particulate matter from a waste stream by the insertion of a perforated surface that retains particles larger that the surface openings and allows the flow through of smaller particles and water (Arundel, 1995). Screen opening size and flow rate capacity are the most important criteria used to select a screen. However many other factors must be considered including plant hydraulics, operational costs, size constraints, debris handing systems, operator qualifications and engineering design (Pankratz, 1995). Common problems associated with screens include mechanical failures and blinding due either to the overloading of the screen or to under sizing of screen gaps. Blinding is defined as the overloading of a screen resulting in the coating over of the open spaces by solids thus preventing the pass-through of water (AWWA, 1977). Screens are classified by the size of the open spaces that allow the passage of water. Screens are classified as coarse, fine, very fine and micro. Table 2.2 shows the range of space openings for each screen size (WEF, 1998).

Table 2.2. Wastewater screen classifications by open space sizes

Type	**Inches (in)**	**Millimeters (mm)**	**Microns (µm)**
Coarse	> 0.25	> 6.0	> 6000
Fine	0.059 - 0.25	1.5 - 6.0	1500 - 6000
Very Fine	0.008 - 0.058	0.2 - 1.49	200 - 1499
Micro	3.9×10^{-8} - 1.2×10^{-2}	0.001 - 0.19	1 - 199

In most poultry slaughter applications screens are used both in parallel and in series. Two larger gap size opening 'primary' screens are typically used in parallel to remove feathers from one flume, while another screen handles solids removal from a separate viscera flume. These primary screens typically range in gap opening size from 1500 to 3500µm (0.059 to 0.138 in) and are designed to remove large offal pieces. Effluent flow from the primary screens is usually combined and then flows through a 'secondary' screen. Commercial secondary rotary screens are commonly available with minimum gap size openings of 500µm (0.020 in) and 250µm (0.010 in). Traditionally, any particulate matter remaining in the wastewater then flows to advanced chemical and/or biological treatment operations for removal prior to discharge.

Membrane filtration

Membrane filtration involves a pressure driven process that uses a semi-permeable membrane to separate particulate matter from wastewater (Strathmann, 1979).

The membrane serves as a selective barrier that allows the passage of water and fine solid particulates (i.e., permeate) while retaining and concentrating the larger solids (i.e., retentate) (de Morais Coutinho et al., 2008). The nature (i.e., texture, structure and material) of the membrane controls which components will permeate and which will be retained, since they are selectively separated according to their molar masses or particle size (Cheryan, 1998).

Ultrafiltration (UF) and microfiltration (MF) are membrane-based, typically pressure driven membrane filtration processes widely used to simultaneously purify, separate and concentrate colloids and high molecular weight materials in water (Cheryan, 1998; Lo et al., 1996). UF membranes have a pore size in the range of 0.001 to 0.1μm, whereas MF membranes have a pore size range of 0.1 to 1.0μm.

UF and MF membranes have found applications in removing particulates, bacteria and pyrogens in water, as well as in recovering valuable ingredients and byproducts in the food, chemical, and pharmaceutical industries (Cheryan and Rajagopalan, 1998). However, limited efforts have been made to recover the byproducts and nutrients from PPW beyond traditional offal screening (El Boushy and van der Poel, 1994; Grant, 1976; Shih and Kozink, 1980). The idea of using UF and MF to recover valuable byproducts from PPW is not new, however since treatment of PPW is usually driven by environmental regulations and not economics, only limited studies on its potential have been conducted (Avula et al., 2009). Shih and Kozink (1980) reported that the combination of UF and dehydration could produce a byproduct that contains 30 to 35% protein and 24 to 45% fat from PPW. Unfortunately, due to the presence of both fat and protein in the feed stream, and the single-stage use of a standalone 30,000MWCO UF membrane unit, the effectiveness of the process was greatly hindered due to severe fouling of the membrane, leaving considerable doubt to its applied full-scale application.

The importance of pretreatment of PPW to remove larger particulates, especially fat, on the performance of membrane-based processes was confirmed by Zhang et al. (1997) in their attempt to investigate the feasibility of recycling chiller water using membranes made from different polymeric materials. The work helped establish the feasibility of recovering protein from PPW using UF by establishing the optimization of processing parameters crucial to overall UF performance. From a processing standpoint, if the optimal filtration conditions are identified, it is highly applicable that a multi-stage MF and UF system could be operated at its highest flux for an extended period of time, minimizing the adverse effects caused by fouled membranes (le Roux and Belyea, 1999; Yushina and Hasegawa, 1994). The importance is that: (1) if the majority of fat in PPW is recovered by primary (physical) treatment steps, a MF and/or UF unit inserted directly following the primary treatment could dramatically reduce the severity of membrane fouling; (2) although fouling of membrane inevitably remains as the primary concern in the recovery of valuable byproducts from PPW, means to restore MF and UF performance (e.g., backwashing) after fouling could be employed in order to make this process cost-effective; and (3) while reducing the organic and nutrient loads of downstream effluent, the recovered protein is expected to retain its quality and functionality because the non-thermal MF and UF operations prevents protein from undergoing thermal denaturation (Avula et al., 2009).

Permeate flux, defined as the permeate flow per unit area per unit time, is the major operating parameter monitored during membrane filtration. Permeate flux is typically reported in the unit of liters per square meter of membrane per hour (Lm^{-2} h^{-1}). The gradual decline in permeate flux is observed during membrane filtration and it is indicative of membrane fouling when all other operating parameters (e.g., pressure, velocity, temperature, concentration) are held constant over an extended period of time (Avula et al., 2009). In 2005 Lo et al., published work on recovery of protein from PPW using UF. In this study the volumetric flux declined rapidly from 264 to 140 Lm^{-2} h^{-1} in the first 20 minutes and continued to drop until the end of the filtration process. The crude protein (CP) concentration of the retentate increased from 80 to 273 mg/L, yielding a concentration ratio of 3.4. This concentration ratio, which was less than the theoretical value of 5.0, is determined by the change in liquid volume after UF, indicates loss of proteins that fouled the polysulfone membrane operating at 25 °C and pH 7.0 S.U.

This initial decrease of flux is typical while using MF and UF to process proteinaceous materials. This is because protein, like fat, does not have a fixed conformation but rather is in a dynamic state where conformation and activity are a compromise between flexibility of structure and stability of the molecules (Campbell et al., 1993). Pressure, and the resulting shear forces, has been identified as one of the major energy inputs required to destabilize such structures in membrane filtration systems (Durchschlag et al., 1996).

Permeate flux is affected by both the temperature and the pH of PPW. In general, the temperature of PPW increases during membrane filtration due to hydraulic turbulence, friction with the membrane, and heat transmitted from the pump. Typically, a cooling coil is used to maintain the operation around 40°C in order to prevent any heat damage to the membrane (Cheryan and Rajagopalan, 1998). It is also well recognized that pH of a solution impacts the conformation of protein molecules. When PPW is acidified with hydrochloric acid from its regular pH of ~6.6 to pH 3.0, it becomes less colloidal and permeate flux significantly increases from 20 to 24 Lm^{-2} h^{-1}, up from 14 to 16 Lm^{-2} h^{-1} (Shih and Kozink, 1980).

Also, the electrical properties of protein molecules play an important role in determining their interactions with the membrane surface (Martínez et al., 2000). Therefore to assess the effect of pH on permeate flux, the isoelectric point (pI) of the protein recovered from PPW needs to be determined. In work published by Martinez et al. (2000), the pI of the recovered protein was found to be at pH 4.6, which was substantially different from the optimal pH value, which was determined at pH 6.74. UF of PPW at pH 6.74 is optimal because it avoids protein coagulation that could result in adverse effects on membrane performance (Lo et al., 2005).

Increases in volumetric feed flow rate are expected to also increase permeate flux in MF and UF systems. However, due to rejection of solutes in a membrane separation process, the excessive increase of flow rate often leads to the problem of the bulk flow carrying away the majority of solution without permitting adequate retention time, causing a poor tangential flow for water removal (Chung et al., 2000). The average flux (J_{ave}) throughout the operation of the membrane filtration unit can be estimated using the following equation (Lo et al., 2005):

$$\mathbf{J_{ave} = 0.33\ Ji + 0.67\ Jr}$$

where Ji is the initial flux and Jr is the fouled flux, with respective leading constants corresponding to the ratio of average time span during a typical MF/UF batch. Under a transmembrane pressure of 96.5 kPa, Lo et al. found the optimum combination of pH and flow rate for PPW was found to be 6.74 and 683mL min^{-1}, respectively.

Membrane characteristics

According to Wagner (2001), membranes can be classified as symmetrical or asymmetrical. Asymmetrical membranes are defined by the internal structure of the membrane and the pores of these materials are usually larger when located further from the filter surface. Conversely, symmetrical membranes have uniform pore sizes in their cross-sections that are identical on both sides of the filter surface.

The main performance characteristics of the any membrane are directly related to pore size (i.e., diameter of openings), solvent density and viscosity, membrane thickness, solvent permeability and porosity. Other factors such as temperature, operating pressure, pH and permeate flow rate also play an essential role in the filtration process (Cheryan and Rajagopalan, 1998; Ostergaard, 1989).

Types of membranes

Membrane filtration processes such as microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO) are used for wastewater treatment (Cheryan and Rajagopalan, 1998). Microfiltration is the physical separation of particles from 0.1 to 10μm under pressure through a semi-permeable membrane. It is used for clarification, sterilization, and to detect or analyze bacteria and other organisms and particulates in wastewater. Nakao (1994) reported MF uses at pressures lower than 0.2 MPa and separation of molecules between 0.025 and 10μm in treating wastewater.

Ultrafiltration is physical separation of large molecules according to their molecular weight under pressure through a semi-permeable membrane (Zeman and

Zydney, 1996) . UF uses pressures lower than 10MPa and separates particles between MWCO values of 1 to 3000Da molar masses (Nakao, 1994). Membranes in the MF and UF ranges are expressed in microns (µm).

Nanofiltration is also a pressure driven process that separate minute molecular particles using a semi-permeable membrane. It is a fairly new development in the range of membrane separation processes. It uses pressures between 1 and 4MPa and separates particles between MWCO values of 350 to 1000Da molar masses (Nakao, 1994). Reverse Osmosis (RO) is the tightest possible membrane process in liquid-liquid separation through a semi-permeable membrane under pressure. It uses pressures between 4 and 10 MPa and separates particles below MWCO value of 350 Da molar masses (Nakao, 1994).

Membrane materials are made up of polymers consisting of either organic or inorganic materials. Organic materials include cellulose acetate (CA), polyamide (PA), polysulfone (PS), polyvinylidene difluoride (PVDF) and ultrafilic. Inorganic materials include metals and ceramics (Cheryan and Rajagopalan, 1998; Cuperus and Nijhuis, 1993; Luque et al., 2008; Nakao, 1994)

Cellulose acetate membrane materials operate effectively at a pH range of 3 to 8 S.U. and a maximum temperature of 50^{o}C. It is used for UF, RO and NF applications (Almas, 1985; Cheryan, 1998). The disadvantage of this membrane material is that they are vulnerable to disinfectants and can be eaten by microorganisms (Cheryan, 1998; Wagner, 2001)

Polysulfone membrane materials have been in use since 1975 for UF and MF. The advantage of this material is its high temperature and pH resistance, however they have low resistance to mechanical compacting (Porter, 1990; Wagner, 2001). PVDF membrane materials have high resistance to hydrocarbons and oxidizing environments (Wagner, 2001).

Ceramic membrane materials are inorganic and are made up of alumina oxide or zirconium oxide placed on graphite material surfaces. Ceramics are resistant to high temperature (over 400^{o}C) and pH (14 S.U.), and support high pressure levels. The downside of these materials is high cost compared to organic membranes (Cuperus and Nijhuis, 1993; Wagner, 2001).

There are also hybrids or combinations of several membranes with different pore size to obtain optimum results in the filtration process. Aider et al. (2008) used continuous electrophoresis with porous membrane (CEPM) to separate organic molecules. This technique can be coupled with dialysis and electrolysis (Bazinet et al., 1998; Langevin and Bazinet, 2011; Nagarale et al., 2006; Tanaka, 2006). An external direct electric field is the driving force for the separation process. Under an electric current effect, the ions (i.e., cations or anions) are transported from one solution to another through a single or multiple semi-permeable membranes. One commonly known form of the electro-separation method is conventional electrodialysis, mainly used in the bio-food industry, biotechnology and nutraceutical industries (Aider et al., 2008).

Factors affecting membrane processes

One major factor affecting membrane performance is the type of filtration flow. The two major types of filtration flow are cross flow and dead-end flow. In cross flow, flow is parallel to the membrane surface whereas in dead-end flow, flow is perpendicular to the membrane surface. The advantage of cross flow is that it does not cause build up or cake formation on the membrane surface and therefore does not suffer as dramatically as dead-end flow from reduced permeate flux overtime (Almas, 1985; Zeman and Zydney, 1996).

During the initial stage of membrane filtration, there is a gradual fall in the permeate flow rate which is mainly attributed to concentration gradient (i.e., concentration polarization) which may lead to gel-layer formation. The gel-layer acts as a 'second membrane' if pressure and the solute concentration in the flow of feed are significantly high. Attempts have been made to explain mass transference through the gel-layer. (Cheryan and Rajagopalan, 1998; Mulder, 1991; Mulder, 1995; Porter, 1990; Roesink et al., 1991; Singh et al., 1998). In the second stage, the flow rate decreases slowly due to the interactions between the membrane pores and the solute, a process known as mechanical fouling. In the final stage, the flow rate is relatively stationary due to interactions between the molecules of the solute and molecules of the membrane leading to adhesion, a process known as physico-chemical interaction (Dresch et al., 1999; Khayat et al., 1997; Marshall and Daufin, 1995). Susanto and Ulbricht (2005; 2009) reported that fouling of a membrane is dependent on the chemical constitution of membrane structure, on the interaction between the solute and membrane and on the interaction between the molecules of the solute. In other words, fouling develops by the adsorption of solute onto the membrane surface, which is determined by the interaction between the solute and membrane.

Blocking of the membrane pores is a result of size and form of the solute in relation to the membrane pore size distribution. Giorno et al. (1998) and Todisco et al. (1996) reported that during internal blockage, chemical species are adsorbed on the inside of the membrane pores reducing the permeate flux. In partial blockage, the pores of the membrane are partial sealed by the solute particles causing reduction in permeate flux. Complete blockage of the membrane pores occurs when the particles on the surface of the membrane are larger than the membrane pore causing no permeate flow.

Membrane cleaning processes

Membrane cleaning processes are essential in filtration since it is essential in developing a membrane's potential technical and economic viability (de Morais Coutinho et al., 2008). To obtain the optimum conditions, the cleaning process is dependent on several factors such pressure, temperature, flow rate, feed concentration, duration of the cleaning and concentration factor. By developing the proper combination of these operational parameters, maximum permeate flow rate and minimal fouling can be obtained (Ebrahim, 1994; Mulder, 1995; Peng and Tremblay, 2008; Smith et al., 2006).

Membrane cleaning can be grouped into four types: physical, chemical, physico-chemical and biological. The most widely used membrane cleaning procedure is the chemical method. Cleaning agents such as alkalis, acids, enzymes, surfactants, sequestering agents, disinfectants and formulated agents have been described in membrane research (Chakrabarty et al., 2010; Cheryan and Rajagopalan, 1998; Hyun, 1997; Smith et al., 2006). Chemical cleaning has several advantages. As an example, alkaline cleaners exhibit no cloud point and therefore cleaning can be accomplished at a high temperature of 82^{o}C. However, there are also several disadvantages to chemical cleaning methods. These include high costs and handling safety problems (Peng and Tremblay, 2008). Ang et al. (2006) investigated the chemical and physical aspects of cleaning organic-fouled RO membranes. The results showed that using a metal chelating agent like disodium ethylenediaminetetraacetate – EDTA Na_2 and an anionic surfactant like sodium dodecyl sulfate – SDS was effective and efficient in reducing the attractive interactive forces induced by the divalent cations - Ca2+ ions between the two fouling-causing agents- alginate and natural organic material (Suwannee River natural organic matter - SRNOM).

Physical methods of cleaning include air sparging (Takizawa et al., 1996), sponge ball cleaning (Yanagi and Mori, 1980), ultrasonication (Kobayashi et al., 2003; Li et al., 2002; Muthukumaran et al., 2007), vibration (Ebrahim, 1994), and backflushing (Kim and Chang, 1991; Levesley and Hoare, 1999; Nakatsuka et al., 1996; Smith et al., 2006). Physical cleaning is dependent on mechanical action to remove foulant particles from the membrane surface. Physical cleaning methods have disadvantages such as difficulty in operation and handling of mechanical cleaning equipment. However, it is often the most preferred method because of its environmental friendliness in that it does not involve the use of chemicals or bioactive agents and does not have chemical supply, storage and handling problems (Peng and Tremblay, 2008).

Backflushing is the physical process of cleaning filters by reversing the flow of fluid through the system. It can be an effective tool in many filtration applications, potentially extending system life and reducing cost (Peng and Tremblay, 2008; Smith et al., 2006). Peng et al. (2005) investigated the use of synthetic bilge water using a cascaded membrane system consisting of a backflushed coalescing MF membrane as a pre-treatment for UF of bilge water. Smith et al. (2006) reported the effect of backflushing in maintaining the flow rate of membrane filtration system to be effective and efficient in removing the majority of the particles responsible for reversible fouling of a membrane and increasing permeate flow rate while reducing the working pressure of the system. In physico-chemical cleaning methods there are chemical additions to the physical process to enhance cleaning effectiveness and efficiency (Ebrahim, 1994; Maartens et al., 2002).

In the every membrane cleaning process, two main steps of rinsing and cleaning are completed. Time, water and cleaning agent consumption play essential roles in these two steps (Heinemann et al., 1988; Kulozik, 1994). The cleaning effect of the rinsing is provided by mechanical action and the power of water. Rinsing is considered an essential step to reduce cleaning agent consumption and to restore permeate flux after cleaning. Cabero et al. (1999) examined the influence of rinsing cleaning procedures in the removal of whey proteins from ceramic membranes.

Biological methods involve the use of cleaning mixtures containing bioagents to enhance the cleaning effectiveness (Peng and Tremblay, 2008). Using enzymes as cleaning agents are also considered biological cleaning (Allie et al., 2003; Argüello et al., 2003; Petrus et al., 2008).

Life Cycle Assessment of Membrane filtration

Life cycle assessment (LCA) is a method to evaluate environmental impacts associated with all the stages of a product's life from the beginning to ending stages (i.e. from raw material stage process through the recycling or disposal stage) (USEPA, 2006). In 1998, Meijers et al. performed a LCA to membrane filtration process used in the production of potable water. In their studies, they found the operational stage was responsible for the majority of environmental problems and the energy consumed in this stage to obtain optimal filtration pressures was of major importance. Also, the use of chemicals such as H_2SO_4 for the cleaning in place proved to cause significant environmental problems. The economic feasibility of incorporating membrane filtration unit in the poultry processing plant indicates positive impacts. Vedavyasan (2007) investigated that even though the capital costs of microfiltration and ultrafiltration are currently 0-25% higher than conventional wastewater treatment systems, and as such their life cycle costs are comparable with conventional treatments.

Physical - Chemical Treatment of PPW

Harper et al. (1988) and WEF (1998) reported that the most popular form of physical-chemical treatment in the U.S. poultry processing plants is dissolved air flotation (DAF). The process of DAF is used to remove the majority of the free O&G and protein from PPW. The removal is achieved by dissolving air in wastewater under pressure and then releasing the pressurized air to form fine bubbles at atmospheric pressure that attach to the suspended fat and protein particles and float then to the surface where they are collected (Kiuru, 2001; Wang et al., 2005). The most important feature of the DAF process is the minute bubble formation (Cassell et al., 1975). DAF systems using chemicals (e.g., alum, ferric sulfate, sodium aluminate and ferrous sulfate) have been shown to remove more than 90% of O&G and solids, and 70% of the BOD load (Rusten et al., 1998) in PPW. Bough et al. (1975) reduced the COD in PPW of a broiler processing plant by 86%. Chemicals enhance the coagulation and flocculation processes in DAF, which are used to separate the suspended solids portion from wastewater (Karpati and Szabo, 1984; Rusten et al., 1998; Travers and Lovett, 1985; Woodard et al., 1972; Woodard et al., 1977). Although, the majority of fat is removed during the DAF treatment, residual fat ranging from 50 to 60 mg/L is found in the post-DAF PPW (Avula et al., 2009).

Poultry processing plants using DAF suffer from the following disadvantages: (1) other than specific rendering operations utilizing the degraded nutrients produced from the DAF process (El Boushy and van der Poel, 1994), only limited efforts have been made to reclaim DAF skimmings (Grant, 1976; Shih and Kozink, 1980); (2) use of chemicals (e.g., metal salts, polymers) in the DAF process makes the precipitated protein useless for many applications (Whittemore, 1994); and (3) potentially valuable constituents in PPW are degraded during the secondary (biological) treatment to biosolids, which in itself presents a disposal problem (Barik et al., 1991; Janosz Rajczyk, 1993).

Biological Treatment of PPW

The most widely utilized biological treatment systems for PPW can be classified as either aerobic (e.g., activated sludge, trickling filters), anaerobic (e.g., covered lagoons, sealed reactors) or facultative (i.e., a combination of aerobic and anaerobic treatment) (Del Nery et al., 2007; Nemerov and Dasgupta, 1991). All biological wastewater treatment processes involve the use of microorganisms (e.g., bacteria) to convert both inorganic and organic materials into a stable biomass and treated effluent (Del Nery et al., 2001)

Aerobic treatment processes such as activated sludge systems are limited by high levels of energy needed for aeration and high sludge volume production (del Pozo et al., 2000; Nguyen and Shieh, 2000). Anaerobic treatment processes have the ability to treat higher strength waste streams as compared to aerobic system, but often required subsequent aerobic treatment to meet environmental regulatory permit limits for effluent discharge.

Biological treatment systems that have been used to effectively treat PPW include sequential batch reactors (SBR), moving bed bioreactors (MBBR), membrane bioreactors (MBR), as well as conventional activated sludge plants (CASP). All these biological treatment systems can achieve more than 90% organic matter removal in PPW.

Sequential batch reactors (SBR) are designed to reduce the organic and nutrient loadings in medium strength wastewater to comply with surface water discharge limits or as a pre-treatment stage to tertiary recycling plants. Oxygen is passed in a form of bubbles through the wastewater to reduce BOD and COD before release into POTWs. The advantages of an SBR include a reduced footprint compared to CASP and since a portion of the biomass is maintained in the reactor after decanting, no sludge recycling system is required. However, the requirement of a settling tank is an important disadvantage due to the lack of physical filtration (Andreottola et al., 2001; Bernet et al., 2000)

Moving bed bioreactors (MBBR) used an activated sludge aeration system where the sludge is collected on carriers (biofilters). These carriers made of plastic have an internal surface for water, air and bacteria contact. The biofiltering process is used for the removal of organic substances, nitrification and denitrification (Pastorelli et al., 1997). This process is quite costly compared to CASP due to increased operation and maintenance (Andreotolla et al., 2000).

The membrane bioreactors (MBR) process involves an activated sludge system that uses membranes for solute separation in place of secondary clarifiers. The membrane component uses low pressure MF or UF membranes. The cost of building, maintaining and operating an MBR is usually high compared to CASP. The disadvantage of this system includes the fouling of the membranes (Bernal et al., 2002).

Conventional activated sludge plants (CASP) involve atmospheric air being introduced to a mixture of primary treated or screened wastewater combined with organisms to develop a biological flocculation which reduces the organic content of the wastewater. The major disadvantages of this process are high energy costs and poor settling of sludge caused by the problematic filamentous microbes. In the presence of inadequate oxygen and iron, the filamentous microbes flourish and cause the biomass to not settle in the clarifier. Also, CASP are poor removers of nitrate and phosphate compounds (Woolard and Irvine, 1995).

The anaerobic treatment process occurs in the absence of free-oxygen (Metcalf and Eddy Inc., 2003). Digestion of organic materials by microorganisms under these conditions results in the production of a gaseous byproduct. This resulting gas mixture, mostly methane and carbon dioxide, with smaller amounts of hydrogen, hydrogen sulfide, and ammonia, is referred to as 'biogas'. Despite the no free-oxygen and low energy requirement during digestion, further treatment with an aerobic treatment process may be needed to meet discharge requirements (Nguyen and Shieh, 2000).

Thesis Goal and Objectives

The goal of this study was to evaluate the effect of membrane filtration on pre- and post-DAF PPW.

The specific objectives were;

1. To evaluate the performance of different membrane pore sizes in Microfiltration (0.1-10µm) and Ultrafiltration (0.01 - 0.1 µm) pore size ranges,

2. To evaluate the performance of three membrane materials; polysulfone (PS), polyvinylidenedifluoride (PVDF) and Ultrafilic,
3. To determine optimum conditions for membrane filtration with respect to flow rate, temperature and operating pressure, and
4. To measure the effect of membrane filtration on chemical oxygen demand (COD), total solids (TS) and total suspension solids (TSS) in PPW.

CHAPTER 3

EFFECTS OF MEMBRANE FILTRATION ON PRE- DAF (DISSOLVED AIR FLOTATION) POULTRY PROCESSING WASTEWATER[1]

[1]Abboah-Afari, E., and B.H. Kiepper. To be submitted to the ASABE Journal *Applied Engineering in Agriculture*

Abstract

An experiment was conducted to measure the effects of membrane filtration on pre-dissolved air flotation (DAF) poultry processing wastewater (PPW). Bulk grab samples of raw PPW were collected after primary (1500–3000µm) and secondary (500µm) offal screens, but before additional wastewater treatment at a commercial broiler processing plant. 4L subsamples of raw PPW were pre-sieved (500/106µm) and then filtered using one of three membranes (0.3µm polyvinylidene difluoride (PVDF), 0.1µm Polysulfone, or 100,000 MWCO Ultrafilic) at one of two pressures (50 or 80 psi) for three 2-hour trials. The resulting 3x2 treatments with 3 repetitions totaling 18 trials were completed over 6 wks, 3 trials taking place one day per wk. Mean chemical oxygen demand (COD) and total solids (TS) concentrations (mg/L) were determined for PPW samples prior to each trial. Mean permeate flux was calculated, and membrane permeate PPW samples were collected at 10 minute intervals during each trial for subsequent COD and TS analyses. Results showed that COD and TS for raw PPW samples (sieved at 500µm) were 5263 mg/L and 3355 mg/L, respectively. COD and TS for pre-sieved PPW samples (sieved to 106µm) were 4390 and 2991 mg/L, respectively, which represented 16.6% and 10.8% reductions, respectively. The maximum mean permeate flux of 115 $Lm^{-2}h^{-1}$ and TS reduction of 34% was obtained by the 0.3µm PVDF membrane, while the maximum mean COD reduction of 89% was achieved by the 100,000MWCO Ultrafilic membrane. Based on a calculated performance index (Pm_i), the 0.3µm PVDF membrane was determined to be the most effective membrane for pre-DAF PPW treatment.

Keywords: *Poultry processing, wastewater, membrane filtration, permeate flux, COD,TS*

Introduction

In 2009, the U.S. poultry industry slaughtered 8.5 billion broilers (USDA, 2010), using an average of 26L (7 gal) of potable water per bird. Thus, the processing of broilers in the U.S. in 2009 generated approximately 2270 million L (60 billion gal) of high strength poultry processing wastewater (PPW) requiring treatment. Current wastewater treatment methods provide viable ways of reducing pollutants such as organics, solids and nutrients in PPW, but often neglect the fact that advanced wastewater treatment alters and adulterates potential valuable poultry processing byproducts (e.g., protein, oil and grease) producing low-value chemical skimmings and biological sludges (Ockerman and Hansen, 2000; Wessels, 1972). Previous analysis of solids recovered from PPW using microscreening have been reported to average 63.5% fat, 17.5% protein, 4.8% crude fiber and 1.5% ash on a dry weight basis (Kiepper et al., 2008).

Dissolved air flotation (DAF) is the most popular physical/chemical PPW treatment method currently utilized by U.S. poultry processors with approximately 80% of slaughter plants employing the technology. Although DAF is effective at PPW treatment, the aggressive aeration of the fine particulates causes excessive oxidative damage and bacterial degradation of fat and protein components. Also, various combinations of chemicals are added to enhance the coagulation and flocculation of the particulates. The combination of this physical and chemical treatment greatly reduces the value of DAF skimmings as a nutrient source in rendered animal byproduct feed ingredients. Moreover, utilization and disposal of DAF skimmings is a major expense and an inconvenience to the poultry industry. Thus, the U.S. poultry processing industry would benefit greatly by PPW treatment technology aimed at recovering unadulterated byproducts prior to DAF treatment (i.e., pre-DAF PPW).

The benefits for pre-DAF PPW treatment include a substantial increase in the volume of unadulterated byproduct (i.e., offal) recovered for rendering with a corresponding reduction in the volume of lower value DAF skimmings produced, substantial chemical cost savings, and reduced energy consumption (Avula et al., 2009).

One emerging technology of interest in treatment of high-strength wastewater is membrane filtration. Even though membrane filtration technology has been studied in various wastewater studies, only limited work has been published on the treatment of PPW. In 2005, Lo et al. successfully recovered concentrated protein from PPW using ultrafiltration (UF). The study was successful, however the work was focused on recovery of a potential high-value byproduct as a retentate rather than the effect membrane filtration had on PPW treatment efficiency.

In membrane filtration, protein and fat exhibit similar characteristics in terms of flexible and stable structures. It is possible that a membrane surface can be operated at its highest flux for a longer time, minimizing the conditions caused by fouled membrane (Cheryan and Rajagopalan, 1998; Yushina and Hasegawa, 1994). Increases in volumetric feed flow rate are expected to increase flux in the membrane filtration system which reduces trapping or retention efficiency. An experiment was conducted to quantify the efficiency of membrane filtration in reducing COD and TS concentration (mg/L) and increase the permeate volume (i.e., flux) in pre-DAF PPW at optimum conditions.

Materials and Methods

Grab samples of approximately 40L of pre-DAF PPW were collected in large plastic containers after the primary (1,500-3,000µm) and secondary (500µm) physical mechanical screens at a north Georgia broiler processing plant during normal slaughter operations and transported immediately to the laboratory. Within 1 hr of collection, 4L subsamples of PPW were poured through a 500µm sieve and designated as 'raw PPW'. Each 4L raw PPW sample was then poured through a 106µm sieve and designated 'pre-sieved PPW' in preparation for membrane filtration trials. The pre-sieved PPW subsamples ranged in temperature from 26-30^{o}C (79-86^{o}F) and pH from 6.0-6.2 S.U.

The experimental trials were carried out using a Spintek STC bench-scale membrane filtration system (Spintek, 2008). As shown in Figure 3.1, this system simulates a full-scale membrane filtration system by circulating raw wastewater from a feed tank, past a sample (i.e., coupon) of flat-sheet test membrane in a cross-current configuration under pressure. A variable speed pump and back pressure control valve can be manipulated to maintain constant pressure on the membrane. The wastewater stream circulates back through the feed tank as a concentrate, while the treated water passes through the membrane as permeate.

The experiment was designed in a 3 x 2 factorial configuration with 3 membrane sizes/materials (100,000MWCO Ultrafilic, 0.10µm Polysulfone and 0.30µm polyvinylidene difluoride (PVDF)), operated at 2 pressure levels (50 and 80 psi) for a total of 6 treatments. The 6 treatments were conducted once per wk for 3 wks for a total of 18 trials. Each test membrane had an effective surface area of 0.005m^2.

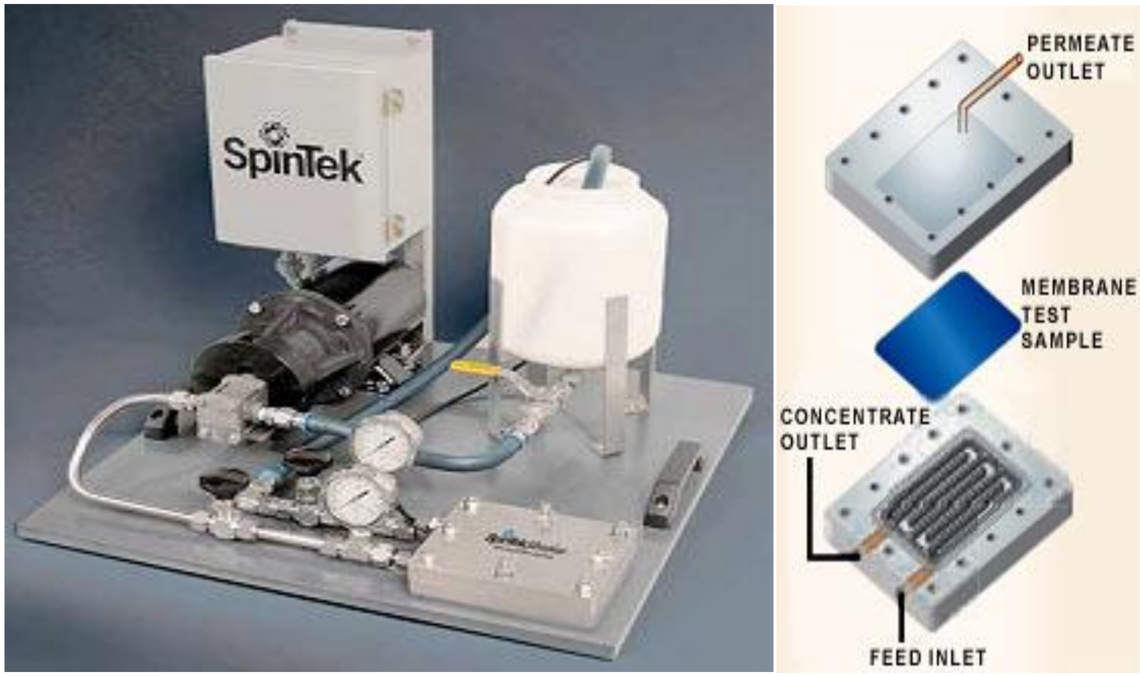

Figure 3.1. SpinTek Static Test Cell (STC) Membrane Filtration System (Spintek, 2008)

Each trial consisted of a 4L pre-sieved subsample of PPW being placed into the feed tank of the STC system fitted with one of the 3 membranes and operated for 2 hours at one of the 2 pressure levels. A total of 16 wastewater samples were collected in 1L glass jars during each trial. Representative raw PPW and pre-sieve PPW samples were collected prior to each membrane filtration trial (i.e., samples 1 and 2). During each trial, membrane filtration permeate samples were collected every 10 minutes (i.e., samples 3-12) with the volume of effluent (mL) noted for subsequent permeate flux calculations. Finally, 1L concentrate samples were collected after 1 and 2 hr (i.e., samples 15 and 16). The pH of all samples was adjusted to < 2.0 S.U. using H_2SO_4 as a preservative and stored at 4^oC prior to analysis.

Analytical Methods

All PPW samples were analyzed for COD (chemical oxygen demand method 5220D) and TS (total solids method 2540B) (APHA, 2005). COD was used to determine the concentration of organic materials in each PPW sample, while the TS test was used to determine the concentration of solids present in each PPW sample.

Statistical Analysis

Data were subjected to statistical analysis by the SAS JMP 8.0.2 program (SAS Institute, 2009). Data from the 3 x 2 treatments with 3 replications were analyzed by factorial ANOVA with membrane at 3 levels and pressure at 2 levels as the main effects. Data was first run as a factorial ANOVA with a main effects (i.e., membrane and pressure) interaction term. If the interaction was not significant (P>0.05), ANOVA was re-run without the interaction term and each factor was analyzed independently. Means were separated using the Tukey-HSD procedure (SAS Institute, 2009). Difference in means were regarded as significant if P<0.05.

Data Analysis

Permeate Flux

Permeate flux is the membrane effluent flow per unit area per unit time. This is the most common calculation used to determine membrane efficiency (Cheryan and Rajagopalan, 1998). In this experiment, permeate flux was calculated and expressed as liters per square meter of membrane per hour ($Lm^{-2}h^{-1}$). The permeate volume collected during each 10 min interval of trial runs was recorded in mL. The total volume (mL) collected for the 10 min interval was divided by 10 to produce a mL/min. This was converted to L/hr and then divided by 0.005 m^2 (i.e., the surface area of each test membrane coupon) to produce the reported permeate flux value ($Lm^{-2}h^{-1}$).

COD and TS Percentage Reduction

Data were analyzed for percentage reduction in concentration of COD and TS. This was achieved by subtracting the end point mean concentration (i.e., pre-sieved or permeate PPW) from the corresponding start point mean concentration (i.e., raw or pre-sieved PPW), and dividing the difference by the start point mean concentration. The result was then multiply by 100%.

Membrane Efficiency

The most effective and suitable membrane for pre-DAF PPW membrane filtration was generated using weighted linear aggregation (WLA) of the three parameters of COD, permeate flux and TS. WLA is a weighted average in which the decision maker assigns the weights of relative importance to each criterion (Eastman et al., 1995). The relative weights of each criterion were computed using a pair-wise comparison matrix (Saaty, 1977). As shown in Table 3.1, the value of each matrix cell represents the relative importance of the row criterion against the column criterion within a range from 1 to 9. A consistency ratio (CR) was used to determine the probability that the matrix ratings were randomly generated which should be less than 0.1. Each relative importance weight was evaluated using the CR. The relative weights are computed by corresponding the maximum eigen value with the relative values of the eigen vector.

Consistency ratio is expressed by $\boldsymbol{CR = \frac{\lambda max - n}{n-1} \geq 0}$

where λ_{max} is the maximum eigen value of the matrix and n is the total number of criteria.

Table 3.1. Pair-wise comparison of the criteria (i.e., COD, Permeate flux, TS) for membrane filtration of pre-DAF poultry processing wastewater

	COD	Permeate Flux	TS	**Weight**
COD	1	3/2	2	**0.46**
Permeate Flux	2/3	1	3/2	**0.32**
TS	1/2	2/3	1	**0.22**

Consistency ratio (CR) = 0.00077

A performance index was used to indicate which of the membranes was the most effective and suitable for the membrane filtration of pre-DAF PPW. Performance index is expressed by $P_{mi} = (w^{cod} \text{ x } R_i^{cod}) + (w^{f} \text{ x } R_i^{f}) + (w^{ts} \text{ x } R_i^{ts})$, where Pm_i = Performance index, w^{cod} and R_i^{cod} = weight and rank of COD, w^f and R_i^f = weight and rank of flux, w^{ts} and R_i^{ts} = weight and rank of TS. Ranks were developed in descending order based on their significant differences (i.e. from the best rank (4) to the least rank (1)).

Results and Discussion

Permeate Flux

Permeate flux ($Lm^{-2}h^{-1}$) values calculated at 10 minute intervals and averaged for the 3 repetitions at each membrane size over the course of the 2 hour STC system trials at 50 and 80 psi are summarized in Table 3.2 and 3.3, and graphically shown in Figures 3.2 and 3.3, respectively. These permeate flux values were in the expected range and are relatively similar to the results reported by Lo et al. (2005).

Table 3.2. Mean permeate flux ($Lm^{-2}h^{-1}$±SEM), COD (mg/L±SEM) and TS (mg/L±SEM) values for 6 membranes filtering pre-dissolved air flotation (DAF) poultry processing wastewater for 120 min

Membrane size/material	Mean Permeate Flux ($Lm^{-2}h^{-1}$±SEM) **(P<0.0001)**	Mean Permeate COD (mg/L±SEM) **(P<0.0001)**	Mean Permeate TS (mg/L±SEM) **(P<0.0001)**
100,000MWCO Ultrafilic	109^{a}±3	465^{b}±13	2324^{b}±61
0.10µm Polysulfone	91^{ab}±3	869^{a}±40	2686^{a}±79
0.30µm PVDF	115^{a}±5	530^{b}±16	1978^{c}±51

a,b, - differing superscripts within a column indicates statistically significant difference (P<0.05)

Table 3.3. Mean permeate flux ($Lm^{-2}h^{-1}$±SEM), COD (mg/L±SEM) and TS (mg/L±SEM) values at 2 pressure levels (50 and 80psi) for pre-dissolved air flotation (DAF) poultry processing wastewater for 120 min

Pressure (psi)	Mean Permeate Flux ($Lm^{-2}h^{-1}$±SEM) **(P<0.0001)**	Mean Permeate COD (mg/L±SEM) **(P<0.0001)**	Mean Permeate TS (mg/L±SEM) **(P=0.3007)**
50	96^{b}±4	682^{a}±33	484±81
80	114^{a}±3	560^{b}±37	359±60

a,b, - differing superscripts within a column indicates statistically significant difference (P<0.05)

Visual inspection of Figures 3.2 and 3.3 show that while the 100,000MWCO Ultrafilic and 0.30µm PVDF membranes flux values produced a flux curve that was downward sweeping and similar results reported by Lo et al. (2005), the 0.10µm Polysulfone membrane did not. At both pressures, the 0.10µm Polysulfone membrane produced flux curves that were relatively flat with only slight increases over the 2-hour trial time period.

Figures 3.2 and 3.3 also showed that the differences between the 3 membranes in flux curves seen over time at the 50 psi level were negated at the 80 psi level. Finally, all trials showed a steady state permeate flux after 2 hours with no visible trend towards blinding for of membranes, with the exception of the 0.10μm Polysulfone membrane at 80 psi which indicates the start of a flux decline at 110 minutes.

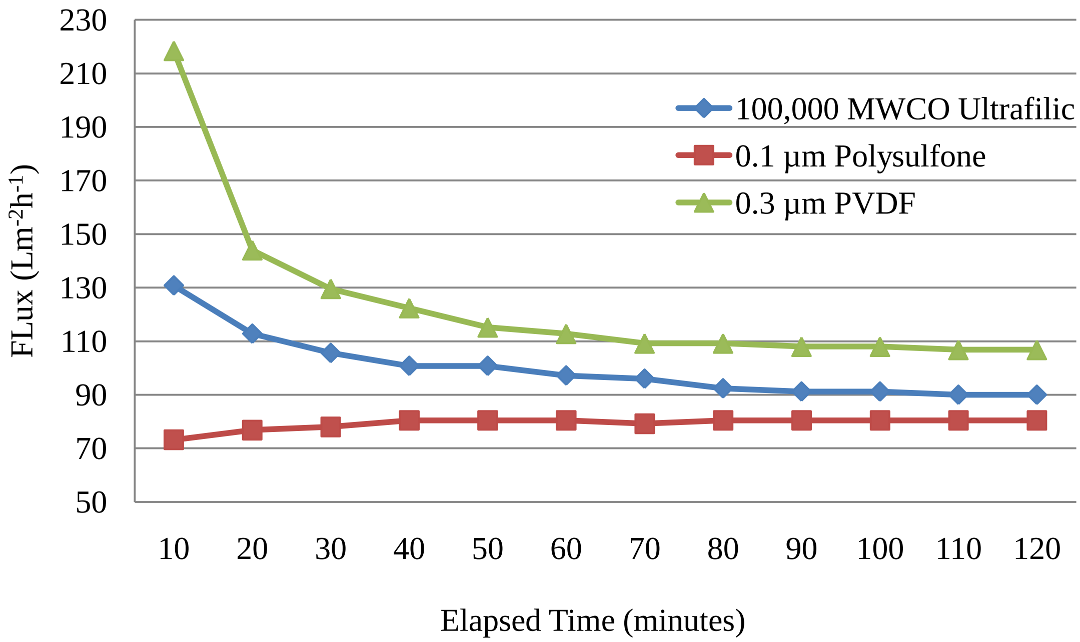

Figure 3.2. Pre-DAF poultry processing wastewater permeate flux ($Lm^{-2}h^{-1}$) values at 10 minute intervals for 3 membrane filters at 50 psi operating pressure

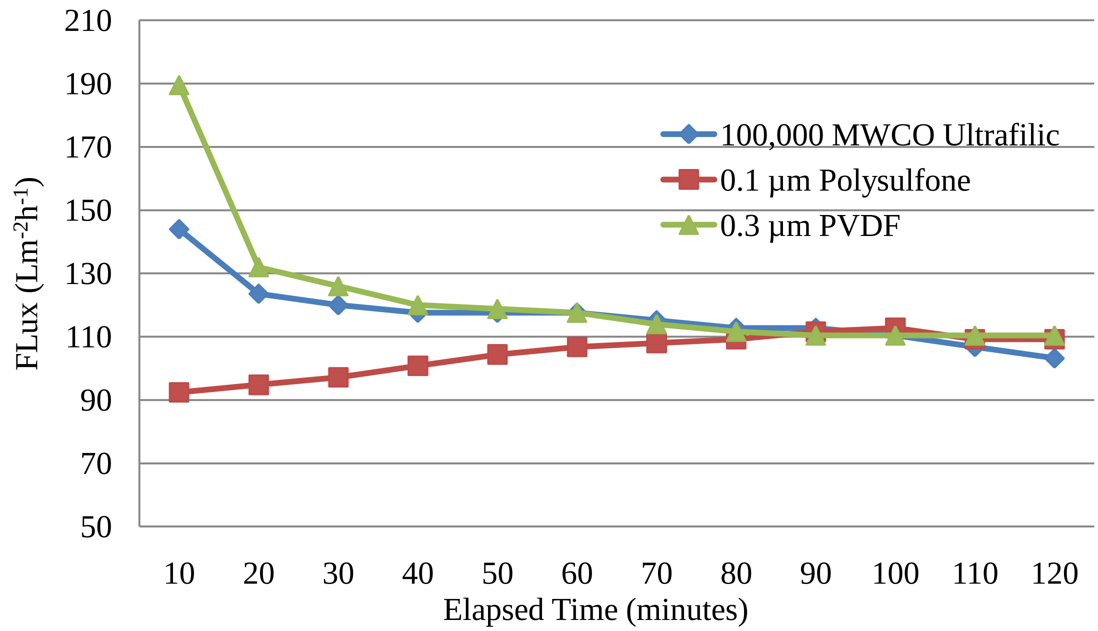

Figure 3.3. Pre-DAF poultry processing wastewater permeate flux ($Lm^{-2}h^{-1}$) values at 10 minute intervals for 3 membrane filters at 80 psi operating pressure

A mean permeate flux value was calculated for each membrane by averaging the twelve (12) 10-minute interval flux values during each trial. Statistical analysis of mean permeate flux results showed no interaction between membrane and pressure (P=0.5293). Therefore, the main effects were analyzed independently. The total mean permeate values at the 3 membrane sizes and the 2 pressure settings are summarized in Figures 3.4 and 3.5.

As shown in Table 3.2 and graphically represented in Figure 3.4, the mean permeate flux values of the 0.30µm PVDF (115 $Lm^{-2}h^{-1}$) and 100,000MWCO Ultrafilic (109 $Lm^{-2}h^{-1}$) membranes were not significantly different, however the mean permeate flux of the 0.10µm Polysulfone (91 $Lm^{-2}h^{-1}$) membrane was significantly lower. As expected, the membrane with the largest nominal gap openings (i.e., 0.30µm PVDF) had the largest total mean flux values, however it was unexpected that the membrane with the next largest nominal gap openings (i.e., 0.10μm Polysulfone) would have the lowest mean flux values. These results would indicate that the membrane material (i.e., Polysulfone) played a significant role in reducing the separation efficiency of the 0.10μm membrane.

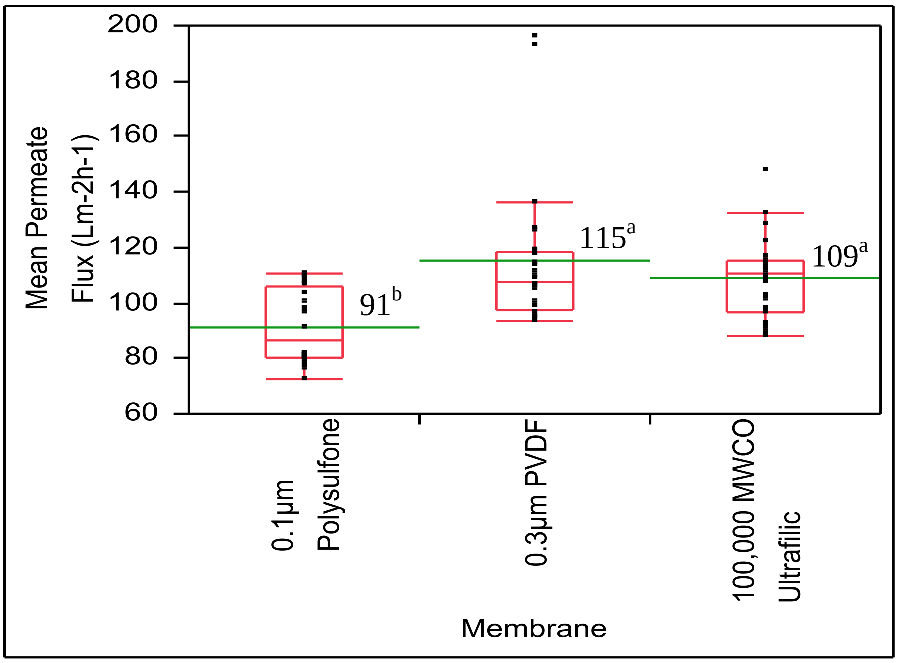

Figure 3.4. Pre-DAF poultry processing wastewater mean permeate flux values ($Lm^{-2}h^{-1}$) for 3 membranes

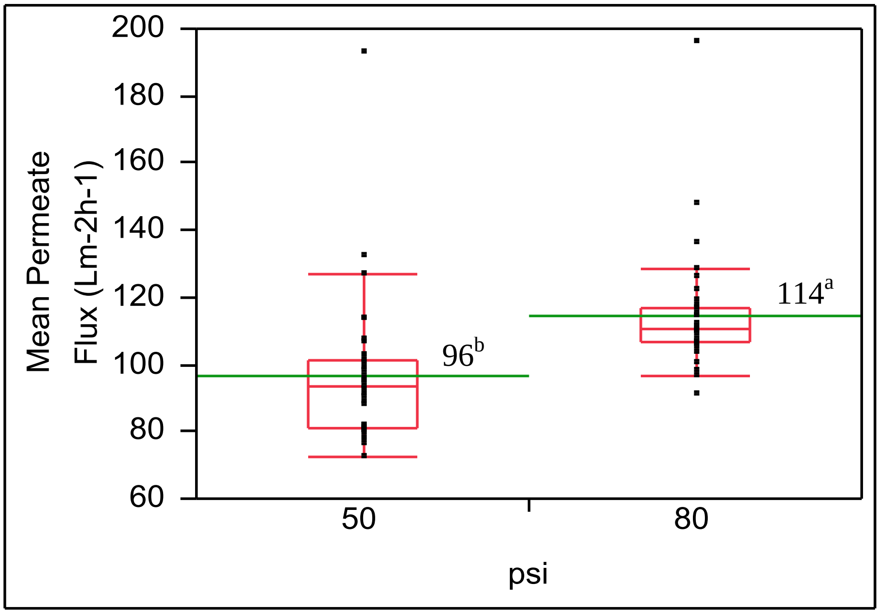

Figure 3.5. Pre-DAF poultry processing wastewater mean permeate flux values ($Lm^{-2}h^{-1}$) for 3 membranes operated at 50 and 80 psi

From the results shown in Table 3.3 and Figure 3.5, the mean permeate flux at 80 psi (114 $Lm^{-2}h^{-1}$) was significantly greater than at 50 psi (96 $Lm^{-2}h^{-1}$). From these results it can be concluded that for the optimum efficiency and high permeate flux, either the 0.3µm PVDF or 100,000MWCO Ultrafilic membrane at 80 psi operating pressure should be selected.

COD Concentration

The concentration (mg/L) of organic matter in each PPW sample was measured using COD. COD concentration data were also used to calculate a COD removal efficiency value, as a percentage (%), for pre-sieved (i.e., 106µm) and membrane permeate PPW samples. The membrane producing the lowest mean COD concentrations and highest COD removal percentages was deemed the most effective.

The mean COD concentrations (mg/L) for raw PPW and pre-sieved PPW samples for the 18 membrane filtration trials were 5263 and 4390 mg/L, respectively. Thus the 106µm pre-sieving reduced the COD concentration on average by 16.6%.

Statistical analysis of mean COD results showed no interaction between membrane and pressure (P=0.7439). Therefore, the main effects were analyzed independently. The mean COD values at the 3 membrane sizes and the 2 pressure settings are summarized in Table 3.2 and 3.3, and graphically represented in Figures 3.6 and 3.7, respectively.

From results shown in Table 3.2 and Figure 3.6, expectantly, the 100,000MWCO Ultrafilic membrane (i.e., the membrane with the smallest nominal gap openings) produced the permeate with the lowest mean COD concentration (465 mg/L), but this value was not significantly different from the 0.30µm PVDF membrane (530 mg/L). The 465 mg/L effluent COD concentration represents an 89% removal efficiency by the 100,000MWCO Ultrafilic membrane as compared with the pre-sieved sample of mean COD concentration of 4390 mg/L.

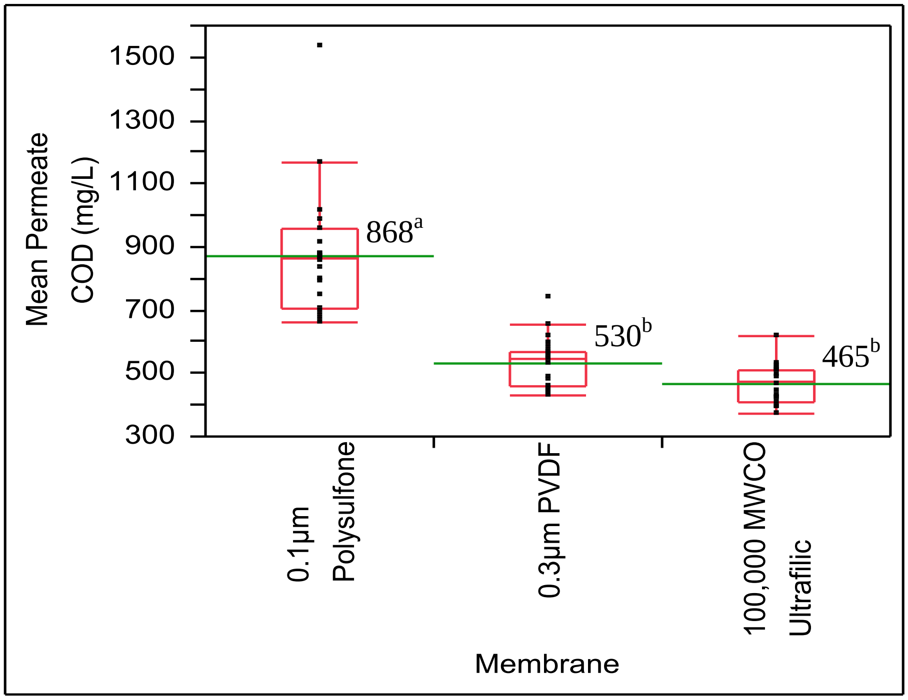

Figure 3.6. Pre-DAF poultry processing wastewater mean permeate COD concentrations (mg/L) for 3 membranes

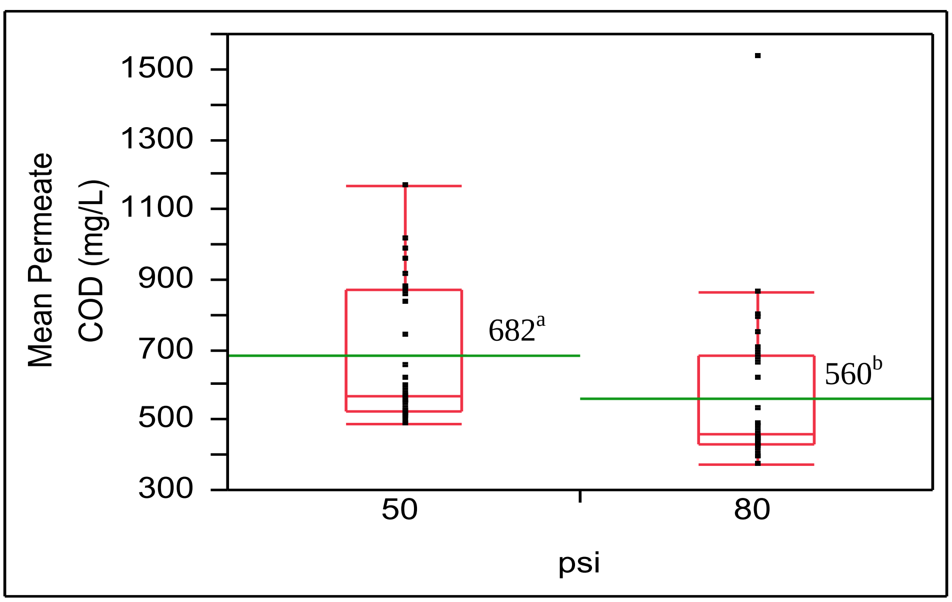

Figure 3.7. Pre-DAF poultry processing wastewater mean permeate COD concentrations (mg/L) at 50 and 80 psi

Unexpectantly, the 0.10μm Polysulfone membrane produced the highest mean COD concentration (868 mg/L), which was significantly higher than both the 0.30μm PVDF and 100,000MWCO Ultrafilic membranes. The 868 mg/L effluent COD concentration represented an 80% removal efficiency as compared with the pre-sieved PPW sample mean COD concentration of 4390 mg/L. With a mean of 530 mg/L of effluent COD concentration, the 0.30μm PVDF had an 88% removal efficiency, while the 465 mg/L effluent concentration of the 100,000MWCO Ultrafilic membrane represented an 89% reduction. Like the permeate flux results, the COD concentration results showed that the 0.10μm Polysulfone membrane was the least efficient producing the highest mean COD values.

Results in Table 3.3 and Figure 3.7 showed that the mean permeate COD concentration at 80 psi (560 mg/L) was significantly better than at 50 psi (682 mg/L). As with permeate flux, from these results it can be concluded that, for the lowest COD permeate concentration and corresponding highest removal efficiencies either the 100,000MWCO Ultrafilic or 0.3μm PVDF membrane at 80 psi operating pressure should be selected.

TS Concentration

The concentration of solids in each PPW sample was measured using TS. TS concentration data were also used to calculate a TS removal efficiency value for pre-sieved (i.e., 106μm) and membrane permeate PPW samples. The membrane producing the lowest mean TS concentrations and highest TS removal percentages was deemed the most effective.

The mean TS concentrations (mg/L) for raw PPW and pre-sieved PPW samples for the 18 membrane filtration trials were 3355 and 2991 mg/L, respectively. Thus the 106µm pre-sieve reduced the TS concentration on average by 10.8%.

Statistical analysis of mean TS results showed significant interaction between the membrane and pressure main effects (P=0.0366). Therefore, the main effects were analyzed simultaneously. The mean TS values at the 3 membrane sizes and the 2 pressure settings are summarized in Table 3.2 and 3.3, and Figures 3.8 and 3.9, while each membrane was analyzed at the 2 pressure levels, as shown in Figures 3.10, 3.11 and 3.12 to determine which membrane/pressure combinations performed best at TS reduction.

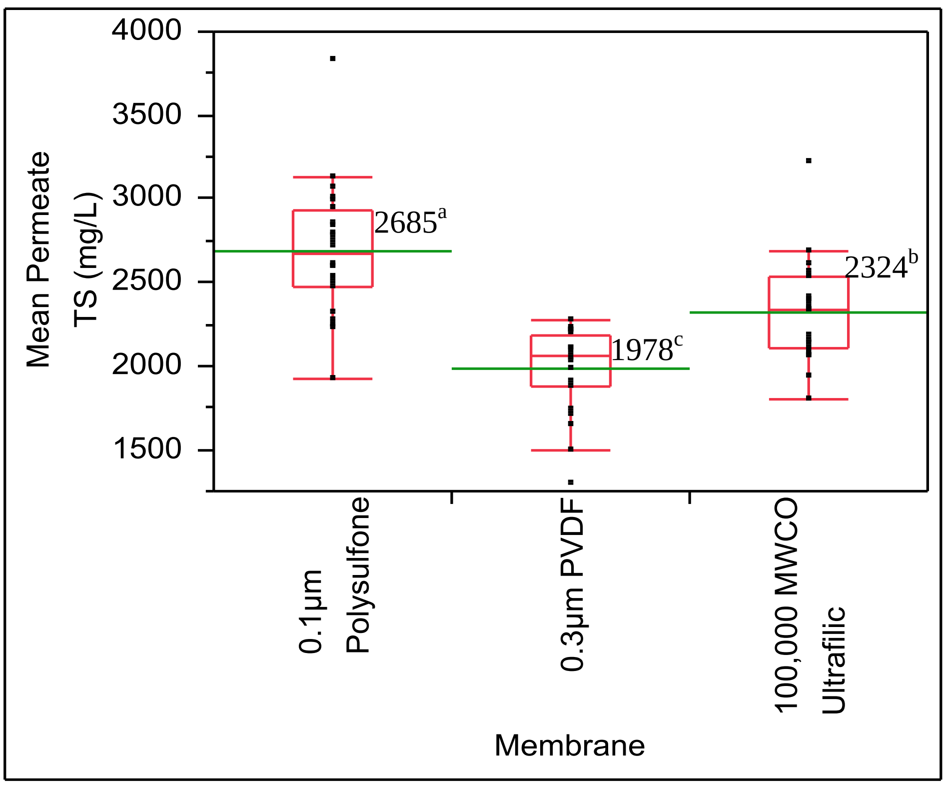

Figure 3.8. Pre-DAF poultry processing wastewater mean permeate TS concentrations (mg/L) for 3 membranes

Surprisingly as shown in Figure 3.8, the 0.30μm PVDF membrane (i.e., the membrane with the largest nominal gap openings) produced the permeate with the significantly lowest mean TS concentration (1978 mg/L) as compared with the two other smaller gap opening membranes. This resulting mean permeate TS concentration represents a removal efficiency of 34% as calculated against the pre-sieved PPW sample mean TS concentration of 2991 mg/L.

The 100,000MWCO Ultrafilic membrane produced a permeate with a mean TS concentration (2324 mg/L) which was significantly lower than the 0.10μm Polysulfone membrane (2685 mg/L). The 100,000MWCO Ultrafilic membrane effluent TS concentration represented a 22% TS removal efficiency, while the 0.10μm Polysulfone membrane had a 10% TS removal efficiency. Like the permeate flux and COD results, the TS mean concentration results showed that the 0.10μm Polysulfone membrane was the least efficient, producing the highest mean TS values. Figure 3.9 shows that the mean permeate TS concentration at 50 psi (2381 mg/L) and 80 psi (2277 mg/L) were not significantly different ($P=0.1481$).

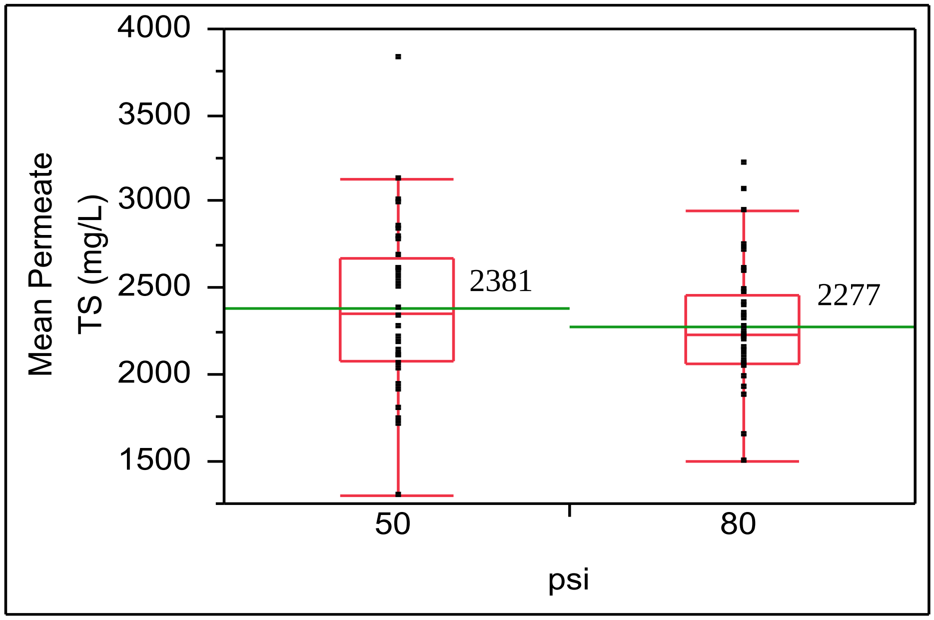

Figure 3.9. Pre-DAF poultry processing wastewater mean permeate TS concentrations (mg/L) at 50 and 80 psi

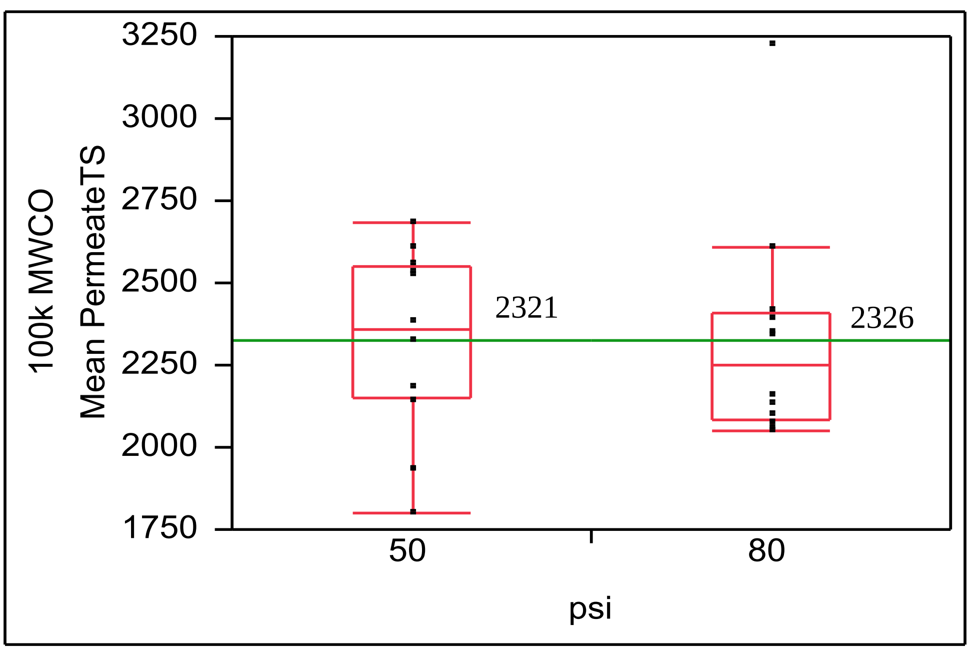

Figure 3.10. Pre-DAF poultry processing wastewater mean permeate TS concentrations (mg/L) for 100,000MWCO Ultrafilic membrane at 50 and 80 psi

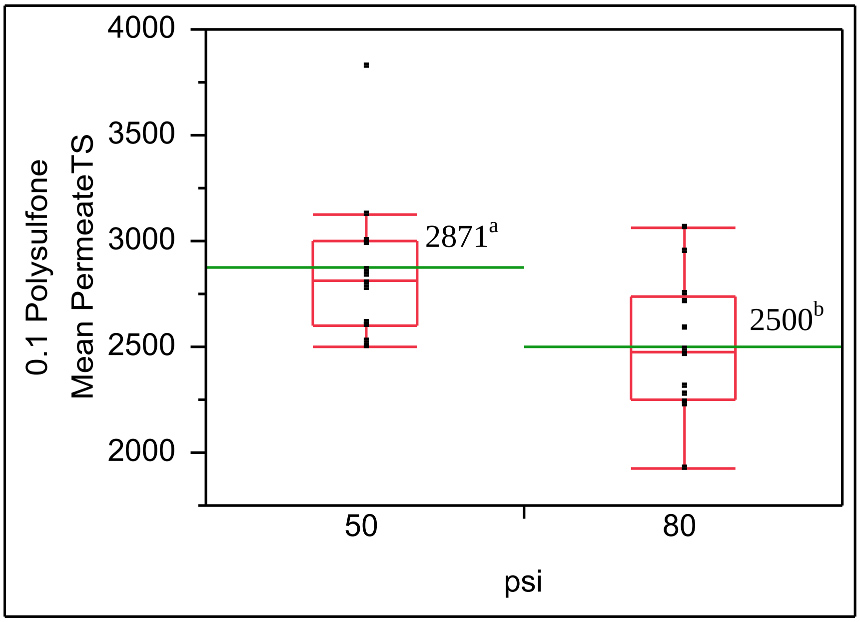

Figure 3.11. Pre-DAF poultry processing wastewater mean permeate TS concentrations (mg/L) for 0.10µm Polysulfone membrane at 50 and 80 psi

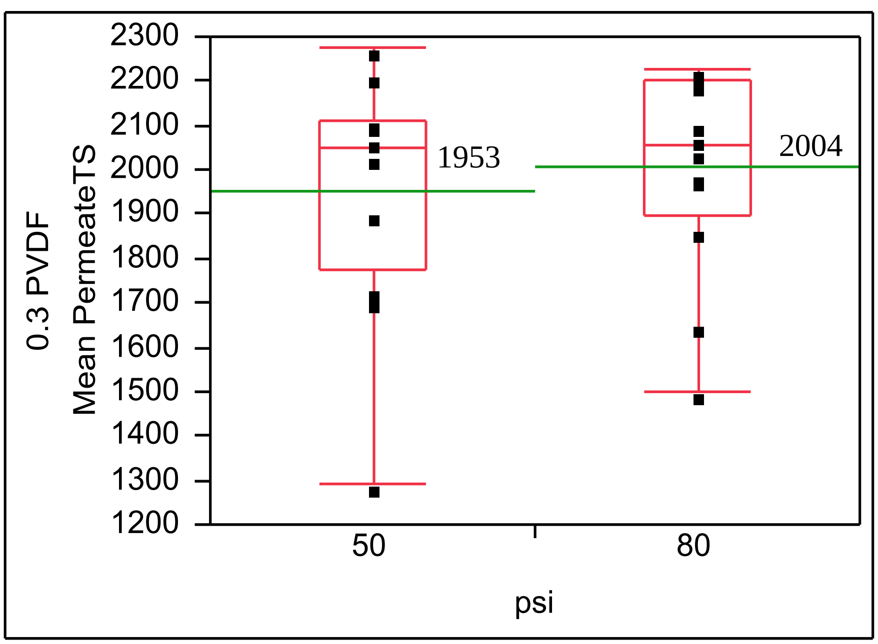

Figure 3.12. Pre-DAF poultry processing wastewater mean permeate TS concentrations (mg/L) for a 0.30µm PVDF membrane at 50 and 80 psi

The mean permeate TS concentrations for each membrane at both pressures are shown in Figures 3.10, 3.11 and 3.12. Results represented in Figures 3.10 and 3.12 showed that there was no significant difference in mean TS concentration for the 100,000MWCO Ultrafilic ($P=0.9676$) and 0.30μm PVDF membranes ($P=0.6246$) at either pressure. The mean permeate TS concentrations for 100,000MWCO Ultrafilic membrane at 50 and 80 psi were 2321 mg/L and 2326 mg/L, respectively. The mean permeate TS concentrations for the 0.30μm PVDF membrane at 50 and 80 psi were 1953 mg/L and 2004 mg/L, respectively. Thus, operating pressure did not significantly affect the TS removal efficiency of either the 100,000MWCO Ultrafilic or 0.30μm PVDF membranes.

However, the mean permeate TS concentration for the 0.10μm Polysulfone membrane at 80 psi (2500 mg/L) was significantly ($P=0.0152$) lower than that at 50 psi (2871 mg/L). These results suggest that operating the 0.10μm Polysulfone membrane at the higher 80 psi pressure will significantly improve TS removal versus the lower 50 psi.

Conclusions

Using the previously described performance index (Pm_i), the most effective membrane for treatment of pre-DAF PPW was determined. Based on calculated Pm_i values as shown in Table 3.4, the 0.3μm PVDF membrane (i.e., the membrane with the largest nominal gap openings) was determined the most effective ($Pm_i = 2.54$ on a 3.0 scale) in regards to increase in permeate flux, and COD and TS reduction. The 100,000MWCO Ultrafilic membrane ($Pm_i = 2.32$) was the second most effective membrane, while the 0.1μm Polysulfone membrane ($Pm_i = 1.32$) was the least effective at pre-DAF PPW treatment. The maximum mean permeate flux of 115 $Lm^{-2}h^{-1}$ and TS reduction of 34% was obtained by the 0.3µm PVDF membrane, while the maximum mean COD reduction of 89% was achieved by the 100,000MWCO Ultrafilic membrane.

Table 3.4. Best performing membrane for treatment of pre-DAF poultry processing wastewater based on maximum permeate flux, and reduction of COD and TS over 120 min of operation based on significant difference (P<0.05)

		COD	Permeate Flux	TS	**Performance Index (Pm_i)**
1	0.3µm PVDF	2	3	3	**2.54**
2	100,000 MWCO Ultrafilic	2	3	2	**2.32**
3	0.1µm Polysulfone	1	2	1	**1.32**

The experiment determined that pre-screening of pre-DAF PPW to 106µm prior to membrane filtration reduced COD by 16.6% and TS by 10.8% making pre-screening a potentially valuable tool in membrane filtration PPW treatment. Membrane filtration of pre-DAF PPW reduced the COD concentration by 80 to 89%, and TS concentration by 10 to 34%. Thus experiment results indicate that membrane filtration in the MF and UF ranges will be substantially more effective at reducing the organic load of pre-DAF PPW as opposed to solids removal.

Mean permeate flux values ($Lm^{-2}h^{-1}$) calculated in this experiment can be used to determine the surface area of membrane (m^2) required to treat a known volume of PPW in a full scale membrane filtration system. As an example, a typical broiler processing plant slaughtering 250,000 birds per day (bpd) and utilizing 26 L per bird will produce 6,500,000 L of PPW. If a membrane filtration system was designed to operate 24 hours per day, then 270,833 L of PPW would need to be treated each hour. Results of this experiment showed the top performing membrane in terms of permeate flux was the 0.3µm PVDF membrane which averaged 115 $Lm^{-2}h^{-1}$. Thus, by dividing 270,833 Lh^{-1} by 115 $Lm^{-2}h^{-1}$ it can be determined that 2355 m^2 would be needed to filter the total PPW stream using 0.3µm PVDF membranes.

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CHAPTER 4

EFFECTS OF MEMBRANE FILTRATION ON POST- DAF (DISSOLVED AIR FLOTATION) POULTRY PROCESSING WASTEWATER[1]

[1]Abboah-Afari, E., and B.H. Kiepper. To be submitted to the ASABE Journal *Applied Engineering in Agriculture*

Abstract

An experiment was conducted to measure the effects of membrane filtration on post-dissolved air flotation (DAF) poultry processing wastewater (PPW). Grab samples were collected and passed through a 500µm sieve and 106µm sieve to prepare the samples for membrane filtration. 4L presieved subsamples were filtered through one of six membranes (30,000MWCO Polysulfone, 30,000MWCO PVDF, 100,000MWCO Ultrafilic, 100,000MWCO PVDF, 0.10µm Polysulfone and 0.30µm PVDF) operated at one pressure level (50 psi) with membrane pore size and membrane material as the main effects. The six treatments were conducted for once per wk for 3 wks for a total of 18 trials. The mean permeate flux values were calculated by averaging the six 10-minute interval flux values from each STC system one hour run. Permeate samples were analyzed for concentration (mg/L) of COD, TS and TSS. Results showed that mean COD, TS and TSS for raw post-DAF PPW samples (sieved to 500µm) were 635, 1706 and 49 mg/L, respectively. Mean COD, TS and TSS for pre-sieved post DAF PPW samples (sieved to 106µm) were 624, 1604 and 48 mg/L, respectively. Thus, pre-sieving reduced COD by 1.7%, TS by 5.9% and TSS by 2.0% prior to membrane filtration. All trials ended with permeate flux in a steady state indicating good resistance to blinding by the membranes. The maximum mean permeate flux value of 224 $Lm^{-2}h^{-1}$ and lowest mean TS value was obtained by the 0.3µm PVDF membrane. The lowest COD concentration, and corresponding highest reduction percentage, was obtained by the 100,000MWCO Ultrafilic membrane (373 mg/L, 40%), which had the highest performance index (Pm_i = 3.56 on a 4.0 scale) of the 6 membranes tested.

Keywords: *Poultry processing, wastewater, membrane filtration, permeate flux, COD, TS, TSS*

Introduction

In 2010, the U.S. Department of Agriculture reported that approximately 8.8 billion broilers were slaughtered in the U.S. with an average live weight per bird of 2.6 kg (5.7 lbs) and a total live weight of 22.7 million metric tons (50.1 billion lbs) (USDA, 2011). It has been reported that U.S. broiler processing plants use 26 L (7 gal) of water during the processing of poultry and the cleaning of plants and equipment (Northcutt and Jones, 2004; Veerkamp, 1999). Treatment and potential reuse of the resulting poultry processing wastewater (PPW) could benefit poultry processing plants by reducing water demand, effluent volume and energy consumption (Avula et al., 2009), while meeting discharge limits set forth in environmental regulatory permits.

A typical poultry processing plant's wastewater treatment system consists of mechanical physical screens (designed to remove inedible offal), DAF (dissolved air flotation) units, and biological treatment provided either onsite (i.e., direct discharge system) or by a public utility (i.e., indirect discharge or pretreatment system). The first treatment process, mechanical physical screening, recovers offal which is a valuable raw material for the rendering industry and is a profit center for poultry processing plants. However, the subsequent treatment processes of PPW such as DAF suffer several disadvantages including effluent containing residual fat in the range of 50 to 60mg/L and adulterated byproducts (e.g., DAF skimmings, biosolids) that have diminished value (Lo et al., 2005), all these costs at the expense of the processor.

Most poultry processors in the U.S. use DAF for treatment of their wastewater (Harper et al., 1988). The concentration or strength of treated wastewater varies from one plant to another depending on the standards set, methods of operations, type of systems and processing loads (Vidal et al., 2000). The process of DAF is used to remove the majority of the free oil and grease (O&G) and particulate protein from PPW. The removal is achieved by dissolving air in the wastewater under pressure and then releasing the pressurized air to form fine microbubbles at atmospheric pressure that adhere to the suspended fats and protein, and float them to the surface where they are collected (Kiuru, 2001). DAF performance is achieved by the number and the size of the air bubbles formed by the pressure relief of the supersaturated air in the wastewater stream (Cassell et al., 1975; Nielsen, 1989). DAF systems using chemicals (e.g. alum, ferric sulfate, sodium aluminate, and ferrous sulfate) can achieve chemical oxygen demand (COD) reductions ranging from 32 to 90% and are capable of removing large amounts of nutrients (Mittal, 2006). Chemicals enhance the coagulation and flocculation processes, which are used to separate the suspended solids from the wastewater.

Using membrane filtration in post-DAF PPW treatment could help further reduce fats, bacteria and other particulate matters (Avula et al., 2009), reduce the cost of operation of biological treatment systems, and lower sludge volume production in direct discharge systems. Membrane filtration could also significantly reduce the amount of surcharge fees paid by indirect or pretreatment dischargers to local utilities for the treatment of their high-strength wastewater streams. Significant reduction in concentration of chemical oxygen demand (COD) and total solids (TS) of PPW by ultrafiltration (UF) was reported by Lo et al. (2005).

There are several factors that influence the effectiveness and efficiency of filtration membranes in treating wastewater. Increase in feed concentration and pressure alters the viscosity, density and diffusivity of the feed solution, thus causing a decrease in permeate flow rate (i.e., flux) (Manjula and Subramanian, 2006). An increase in temperature results in a decrease in fluid viscosity and increase in molecular diffusivity through the membrane (Cheryan and Rajagopalan, 1998; Marenchino, (2006).; Nakao, 1994; Zak and Pawlak, 2006; Zhang and Song, 2000).

Membrane material also affects membrane performance. For example, Polysulfone has exceptional temperature (up to 75^{o}C) and pH (1 to 13 S.U.) resistance, but has been known to perform poorly in the treatment of protein-based food processing wastewater streams. There should be balance between membrane performance with respect to permeate flow rate and retention of the desired solute and membrane characteristics such as tendency for fouling, cost and life span (Cheryan and Rajagopalan, 1998).

Many variables, such as composition of membrane, method of membrane manufacturing, shape and configuration of the fluid molecules, their interactions with each other and the membrane surface, fluid dynamics of the membrane unit, pressure, temperature and velocity of the mixture, influence the filtration process (Del Nery et al., 2007). Two of the main factors that control the efficiency of membrane separations are size exclusion and chemical interaction between membrane surfaces and permeate.

An experiment was conducted to investigate the efficiency of the treatment of post-DAF PPW using membrane filtration. Permeate flux, COD, TS and total suspension solids (TSS) were measured and analyzed. The performance of 6 membranes (4 pore sizes and 3 membrane materials) within the microfiltration (MF) and UF ranges were evaluated at 50 psi.

Materials and Methods

Sample Collection and Preparation

Grab samples of approximately 40L of post-DAF PPW were collected in large plastic containers after primary screening and pretreatment in a DAF unit at a north Georgia broiler processing plant during normal slaughter operations and transported immediately to the laboratory. The DAF process has been shown to remove more than 90% of fats and solids in PPW (Grant, 1980; Nielsen, 1989). Within 1 hr of collection and in preparation for each experimental trial, 4L subsamples of PPW were poured from the collection containers through a 500µm sieve and designated as ‘raw PPW’. Each 4L raw PPW sample was then poured through a 106µm sieve and designated ‘pre-sieved PPW’. Pre-sieved subsamples ranged in temperature from 18 to 34^{o}C (64 to 93^{o}F) and pH ranged from 5.0 to 5.6 S.U.

Each experimental trail was conducted using one of 6 membranes (30,000MWCO Polysulfone, 30,000MWCO PVDF, 100,000MWCO Ultrafilic, 100,000MWCO PVDF, 0.10µm Polysulfone and 0.30µm PVDF) within the microfiltration (MF) and ultrafiltration (UF) ranges, operated at one pressure level (50 psi) with membrane material and membrane pore size as the statistical main effects. The 6 membranes (i.e., treatments) were tested once per week for 3 weeks for a total of 18 trials. The experiment was carried out using a Spintek STC bench-scale membrane filtration system as shown in Figure 4.1.

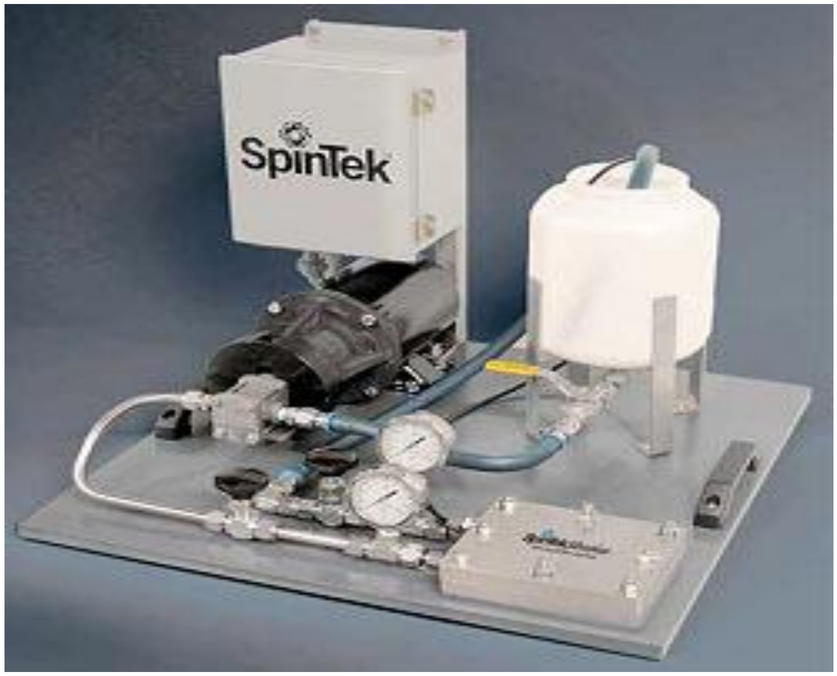

Figure 4.1. SpinTek Static Test Cell (STC) Membrane Filtration System (Spintek, 2008)

This system simulates a full-scale membrane filtration system by circulating raw wastewater from a feed tank, past a sample (i.e., coupon) of flat-sheet test membrane in a cross-current configuration under pressure. A variable speed pump with a maximum speed of 1207 rpm and back pressure control valve can be manipulated to maintain constant pressure on the membrane. For this experiment the pressure remained constant at 50 psi. The wastewater stream circulates back through the feed tank as a retentate (i.e., concentrate), while the treated water passes through the membrane as permeate. The flow through the STC system during the experiment ranged from 2.3 to 2.6 L/min. Each test membrane coupon had an effective surface area of $0.005m^2$.

Each trial consisted of a 4L pre-sieved subsample of PPW being placed into the feed tank of the STC Membrane Filtration System fitted with one of the 6 membranes (previously rinsed with deionized water) and operated for 60 min at 50 psi. The 6 trials were randomly conducted each week for 3 weeks. A total of 9 wastewater samples were collected in 1L glass jars during each trial. Representative raw PPW (500µm) and pre-sieve (106µm) PPW samples were collected prior to each membrane filtration trial (Samples 1 and 2). During each trial, membrane filtration permeate samples were collected every 10 minutes (Samples 3 – 8) with the volume (mL) of effluent noted for subsequent permeate flux calculations. Finally, a sample of recycled concentrate was collected after 60 min (Sample 9). The pH of all samples was adjusted to < 2.0 S.U. using H_2SO_4 as a preservative and stored at 4^oC prior to analysis.

Analytical Methods

The post-DAF PPW samples were analyzed for COD (chemical oxygen demand method 5220D), TS (total solids method 2540B) and TSS (total suspended solids method 2540D) concentration (mg/L) (APHA, 2005). A COD test was run on each 10 min interval permeate sample collected and was used to determine the organic 'strength' of post-DAF PPW. A TS test was also run on each 10 min interval permeate sample collected and was used to determine the concentration (mg/L) of total solids present in each sample. Due to the small amount of permeate sample available following COD and TS analysis, a composite of the 10 minute interval permeate samples for each trail was prepared and a TSS test was run on each composite sample to determine the concentration (mg/L) of suspended solids present. TS can be defined in terms of particulate size as the sum of TSS and total dissolved solids (TDS) as represented in the equation: TS = TSS + TDS (APHA, 2005).

Statistical Analysis

Data were subjected to statistical analysis by the SAS JMP 8.0.2 program (SAS Institute, 2009). Data from the 6 membranes (30,000MWCO Polysulfone, 30,000MWCO PVDF, 100,000MWCO Ultrafilic, 100,000MWCO PVDF, 0.10µm Polysulfone and 0.30µm PVDF) with 3 replications were analyzed by one-way ANOVA procedures for completely randomized design. Means were separated using Tukey-HSD procedure to assess the significance ($P<0.05$) of the data (SAS Institute, 2009).

Data Analysis

Permeate Flux

Permeate flux is defined as the membrane effluent flow per unit area per unit time and is the most common calculation used to determine membrane efficiency (Cheryan and Rajagopalan, 1998). In this experiment, permeate flux was calculated and expressed as liters per square meter of membrane per hour ($Lm^{-2}h^{-1}$). The permeate volume collected during each 10 min interval of trial runs was recorded in mL. The total volume (mL) collected for the 10 min interval was divided by 10 to produce a mL/min value. The mL/min value was then divided by 1000 to produce a L/min value. The L/min value was then multiplied by 60 to produce a L/hr value. Finally, the L/hr value was divided by 0.005 m^2 (i.e., the surface area of each test membrane coupon) to produce the reported permeate flux value ($Lm^{-2}h^{-1}$).

COD, TS and TSS Percentage Reduction

Percentage reduction in concentrations (mg/L) of analytical tests was calculated by subtracting the end-point (i.e., pre-sieved or permeate) values from the corresponding start-point (i.e., raw or pre-sieved) values, and dividing the difference by the start-point value. The result was then multiply by 100%.

Membrane Efficiency

The most effective and suitable membrane for post-DAF PPW treatment was generated using weighted linear aggregation (WLA) of 3 of the parameters tested (i.e., COD, permeate flux and TS). TSS results were not utilized in the WLA due to non-significance statistically. The WLA is a weighted average in which the decision maker assigns the weights of relative importance to each criterion (Eastman et al., 1995). The relative weights of each criterion was computed using a pair-wise comparison matrix (Saaty, 1977). As shown in Table 4.1, the value of each matrix cell represents the relative importance of the row criterion against the column criterion with a range from 1 to 9. A consistency ratio (CR) was used to determine the probability that the matrix ratings were randomly generated, which should be less than 0.1. Each relative importance weight was evaluated using the CR. The relative weights are computed by corresponding the maximum eigen value with the relative values of the eigen vector.

Consistency ratio is expressed by $\boldsymbol{CR = \frac{\lambda max - n}{n-1} \geq 0}$

where λ_{max} is the maximum eigen value of the matrix and n is the total number of criteria.

Table 4.1. Pair-wise comparison of the criteria (i.e., COD, Permeate flux, TS) for membrane filtration of post-DAF poultry processing wastewater

	COD	Permeate Flux	TS	**Weight**
COD	1	3/2	2	**0.46**
Permeate Flux	2/3	1	3/2	**0.32**
TS	1/2	2/3	1	**0.22**

Consistency ratio (CR) = 0.00077

A performance index was used to indicate which of the membrane was the most effective and suitable for the membrane filtration of post-DAF PPW.

Performance index is expressed by $\boldsymbol{P_{mi}} = \left(\boldsymbol{w^{cod}}\ \boldsymbol{x}\ \boldsymbol{R_i^{cod}}\right) + \left(\boldsymbol{w^{f}}\ \boldsymbol{x}\ \boldsymbol{R_i^{f}}\right) + \left(\boldsymbol{w^{ts}}\ \boldsymbol{x}\ \boldsymbol{R_i^{ts}}\right)$

where P_{mi} = Performance index, w^{cod} and R_i^{cod} = weight and rank of COD, w^{f} and R_i^{f} = weight and rank of flux, w^{ts} and R_i^{ts} = weight and rank of TS. Ranks were developed in descending order based on their significant differences (i.e. from the best rank (4) to the least rank (1)).

Results and Discussion

Permeate Flux

The mean permeate flux values for each trail were calculated by averaging the six 10-minute interval flux values from each STC system run for a period of one hour. The resulting means from the 3 repetitions were then averaged to determine an overall permeate flux mean for each membrane. The overall mean permeate flux ($Lm^{-2}h^{-1}$) values for the 6 membranes at 50 psi operating pressure are summarized in Table 4.2 and graphically shown in Figures 4.2 and 4.3.

Visual inspection of Figure 4.2 showed that all membranes flux values produced a downward sweeping flux curve similar to Lo et al. (2005), with a much steeper curve from the 0.30µm PVDF membrane versus the other membranes which remained relatively flat throughout the run.

As shown in Table 4.2 and graphically represented in Figure 4.3, the 0.30µm PVDF (224 $Lm^{-2}h^{1}$), 100,000MWCO PVDF (149 $Lm^{-2}h^{-1}$) and 0.1µm Polysulfone (146 $Lm^{-2}h^{-1}$) membranes were not significantly different from each other, nor were the 30,000MWCO Polysulfone (114 $Lm^{-2}h^{-1}$), 100,000MWCO Ultrafilic (100 $Lm^{-2}h^{-1}$) and

30,000MWCO PVDF (84 $Lm^{-2}h^{-1}$) membranes. However, the mean permeate flux of the 0.3μm PVDF membrane was significantly higher than the 30,000MWCO Polysulfone, 100,000MWCO Ultrafilic and 30,000MWCO PVDF membranes.

Table 4.2. Mean permeate flux ($Lm^{-2}h^{-1}$±SEM), COD (mg/L±SEM), TS (mg/L±SEM) and TSS (mg/L±SEM) values for 6 membranes filtering post-dissolved air flotation (DAF) poultry processing wastewater for 60 min

Membrane size/material	Mean Permeate Flux ($Lm^{-2}h^{-1}$±SEM) **(P<0.0001)**	Mean Permeate COD (mg/L±SEM) **(P<0.0001)**	Mean Permeate TS (mg/L±SEM) **(P<0.0001)**	Mean Permeate TSS (mg/L±SEM) **(P=0.1984)**
30,000MWCO Polysulfone	114^{b}±6	388^{cd}±8	2292^{ab}±209	21±12
30,000MWCO PVDF	84^{b}±2	397^{cd}±13	2863^{a}±172	29±5
100,000MWCO Ultrafilic	100^{b}±1	373^{d}±11	2332^{ab}±116	8±2
100,000MWCO PVDF	149^{ab}±7	483^{bc}±32	1925^{bc}±208	12±4
0.10μm Polysulfone	146^{ab}±4	748^{a}±42	2020^{bc}±55	24±3
0.30μm PVDF	224^{a}±59	519^{b}±12	1498^{c}±133	13±6

a,b,c,d - differing superscripts within a column indicates statistically significant difference (P<0.05)

As expected, the membrane with the largest nominal gap openings (i.e., 0.30μm PVDF) had the largest mean flux values, while the 2 membranes with the smallest nominal gap openings (i.e., 30,000MWCO) and one of the next smallest nominal gap opening membranes (i.e., 100,000MWCO) had the significantly lowest mean flux values. These results indicate that membrane pore size (i.e., 0.30μm versus 100,000 MWCO and 30,000MWCO) plays a critical role in determining the permeate flow rate of membranes. Results also showed that the membrane materials of the 100,000MWCO membranes (i.e., PVDF and Ultrafilic) and the 30,000MWCO membranes (i.e., Polysulfone and PVDF) did not play a significant role in mean permeate flux. From the results shown in Table 4.2, it can be concluded that, for the optimum efficiency and high permeate flux, either the 0.3µm PVDF, 100,000MWCO PVDF or 0.10µm Polysulfone membrane should be selected.

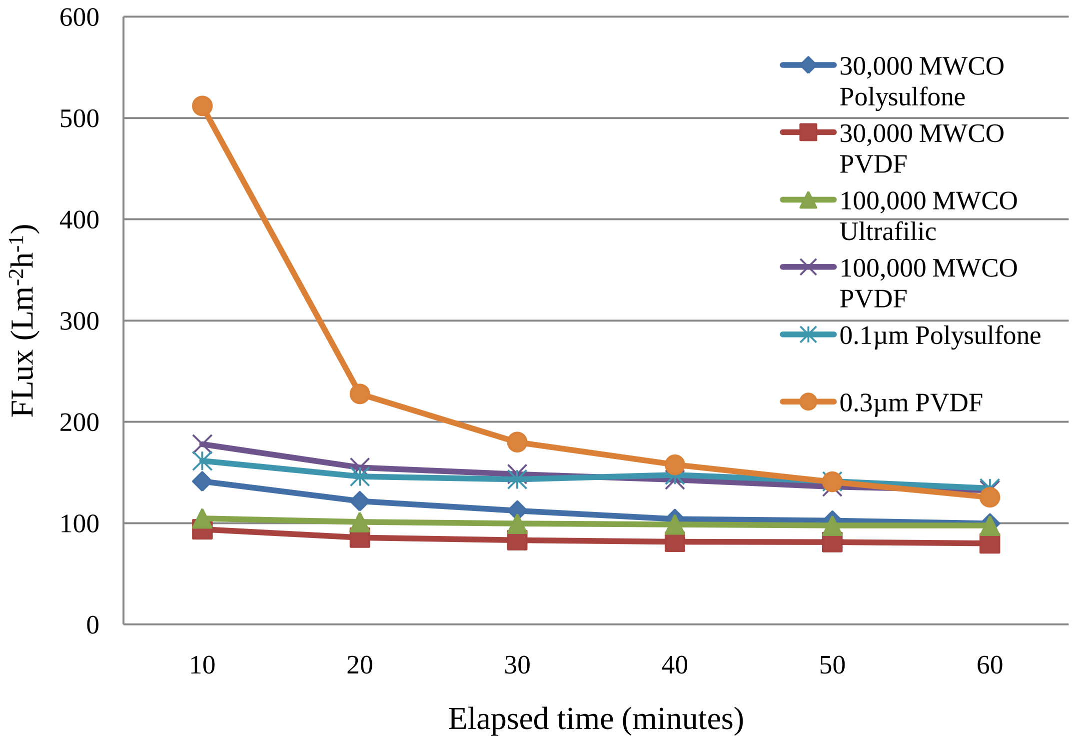

Figure 4.2. Post-DAF poultry processing wastewater permeate flux ($Lm^{-2}h^{-1}$) values at 10 min intervals for 6 membrane filters over 60 min

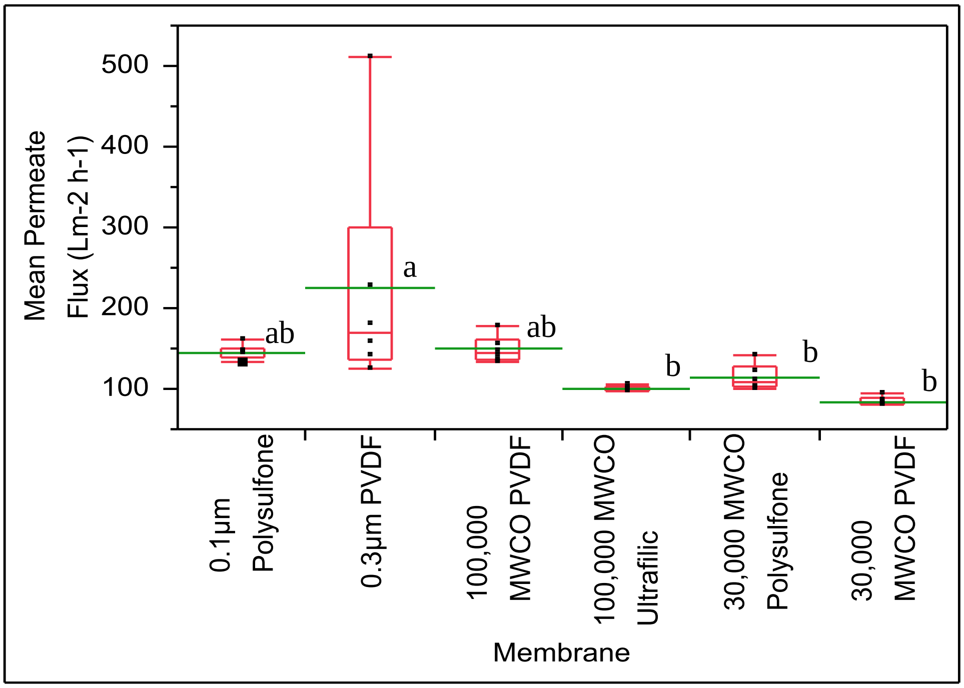

Figure 4.3. Mean permeate flux ($Lm^{-2}h^{-1}$) values for 6 membranes filtering post-DAF poultry processing wastewater over 60 min

COD Concentration

The organic strength of the post-DAF PPW samples was measured using COD. Mean permeate COD concentrations (mg/L) were determined and analyzed for the 6 membranes. COD concentration (mg/L) data were also used to calculate a COD removal efficiency (%) values for the pre-sieved and membrane permeate PPW samples. Statistical analysis showed that there were significant differences in the COD concentration means (P<0.0001). The COD results are summarized in Table 4.2 and graphically represented in Figures 4.4 and 4.5. The membrane producing the lowest mean COD concentrations and highest COD removal percentages was deemed the most effective.

The mean COD concentrations (mg/L) for raw PPW (i.e., sieved at 500µm) and pre-sieved PPW samples (i.e., sieved at 106µm) for the 18 membrane filtration trials were 635 and 624 mg/L, respectively. Thus the 106µm pre-sieving reduced the COD concentration on average by 2%.

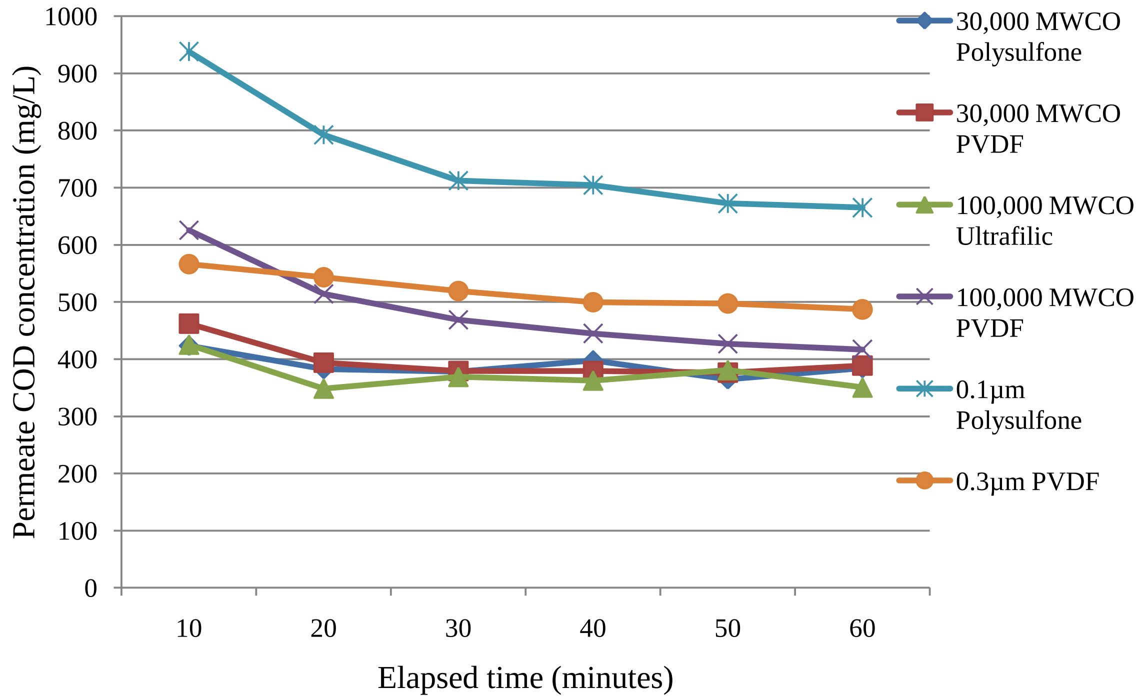

Figure 4.4. Post-DAF poultry processing wastewater mean permeate COD concentrations (mg/L) values at 10 min intervals for 6 membrane filters over 60 min

Visual inspection of Figure 4.4 showed that all of the membrane mean COD values produced a slight downward sweeping curve. The downward curve is indicative of improving COD removal over the course of the filtration run. As shown in Table 4.2 and Figure 4.5, the 0.1µm Polysulfone membrane had the highest COD permeate concentration (748 mg/L), which was significantly higher than all the other membranes. This established the 0.1µm Polysulfone membrane as the least efficient at COD reduction and the only membrane with a negative removal efficiency (i.e.,-20%), indicating that the Polysulfone membrane material degenerated in some way when in contact with PPW, thus adding COD to the permeate stream. There was no significance difference between the 0.30µm PVDF membrane (519 mg/L) and the 100,000MWCO PVDF (483 mg/L), which represented removal efficiencies of 17% and 23%, respectively. There was also no significant difference between the 100,000MWCO PVDF, 30,000MWCO PVDF (397mg/L) and 30,000MWCO Polysulfone (388 mg/L) membranes, which had removal efficiencies of 23%, 36% and 38%, respectively. Finally, the 100,000MWCO Ultrafilic (373 mg/L) membrane produced the lowest COD mean concentrations, although not significantly different from the 30,000MWCO PVDF or the 30,000MWCO Polysulfone membranes. The 373 mg/L permeate COD concentration produced by the 100,000MWCO Ultrafilic membrane resulted in the highest COD removal efficiency of 40% making it the most effective COD reduction membrane.

Interestingly, the 30,000MWCO PVDF (36% COD reduction) and 30,000MWCO Polysulfone (38% COD reduction) membranes were not significantly different, indicating that membrane material did not influence the COD removal efficiency at the smaller gap opening size. This result is surprising since the Polysulfone membrane material seems to have a strong detrimental effect on the removal efficiency of the 0.1µm membrane which produced a negative % reduction. However in the case of the 100,000MWCO membranes, membrane material seems to play a significant role in that the Ultrafilic membrane material (40% COD reduction) significantly outperformed the PVDF membrane material (23% COD reduction). From the results in Table 4.2, it can be concluded that, based on the lowest mean COD mean concentration and highest COD mean removal percentages, either the 100,000MWCO Ultrafilic, 30,000MWCO PVDF or 30,000MWCO Polysulfone membranes membrane should be selected.

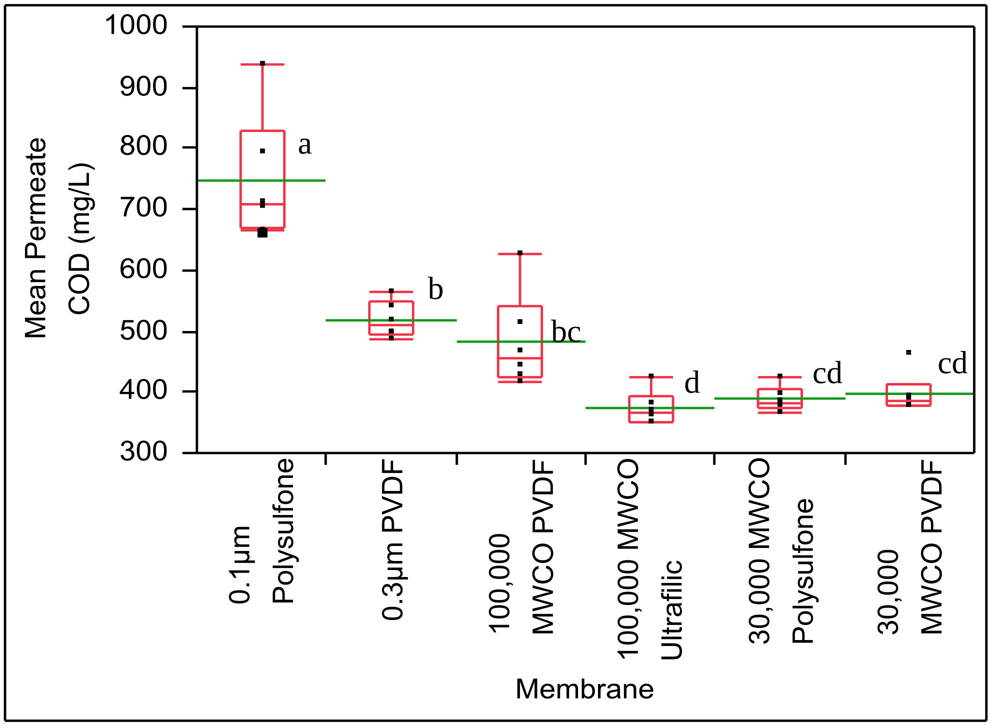

Figure 4.5. Mean permeate COD concentrations (mg/L) for 6 membranes filtering post-dissolved air flotation (DAF) poultry processing wastewater for 60 min

TS Concentration

The total amount of solids contained in the PPW membrane permeate samples was measured using TS. TS mean concentration (mg/L) data for each membrane was determined and analyzed. These data were also used to calculate a TS removal efficiency (%) value for pre-sieved and membrane permeate PPW samples. The membrane producing the lowest mean TS concentrations and highest TS removal percentages was deemed the most effective. Statistical analysis showed that there were significant differences in the TS concentration permeate means (P<0.0001). The TS results are summarized in Table 4.2 and Figure 4.6.

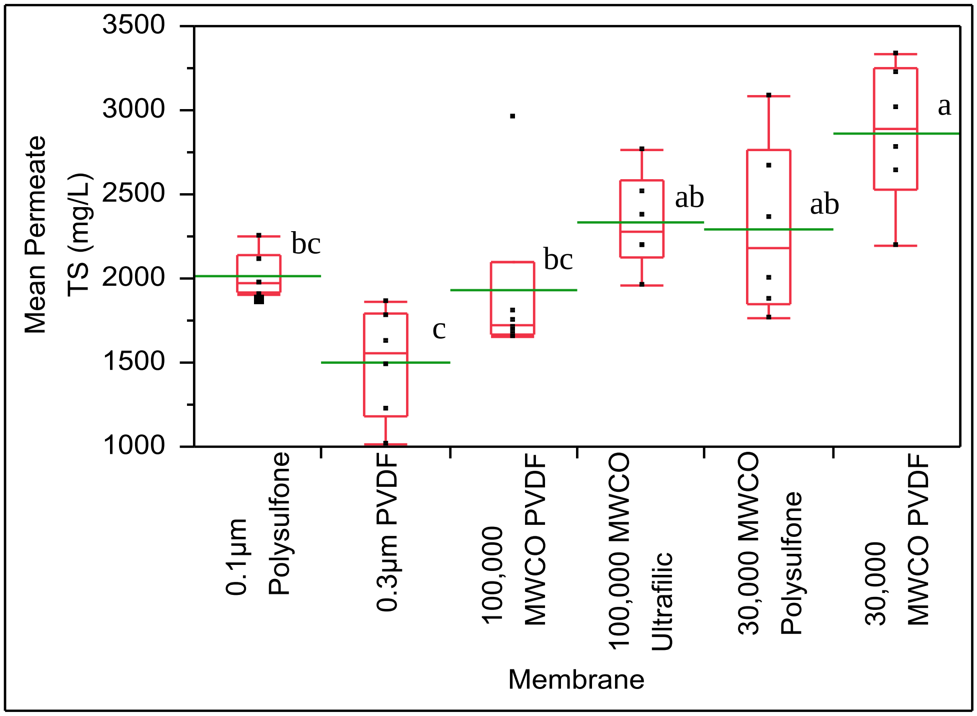

Figure 4.6. Mean permeate TS (mg/L) for 6 membranes filtering post-DAF poultry processing wastewater for 60 min

The mean TS concentrations (mg/L) for raw PPW and pre-sieved PPW samples for the 18 membrane filtration trials were 1706 and 1604 mg/L, respectively. Thus the 106µm pre-sieve reduced the TS concentration of the post-DAF PPW on average by 6%. It should be noted that only one membrane (i.e., 0.3µm PVDF) produced a positive removal efficiency for TS of 7%. The 5 remaining membranes all produced mean TS permeate concentrations which were higher than the initial trial pre-sieved PPW samples. This would indicate that the membranes themselves, in contact with PPW, release particulates into the permeate stream causing TS concentrations to rise.

As shown in Figure 4.6, the 30,000MWCO PVDF (2862 mg/L), 100,000MWCO Ultrafilic (2332 mg/L) and 30,000MWCO Polysulfone (2292 mg/L) membranes were not significantly different from each other, and were the least efficient membranes at reducing TS. The 0.1µm Polysulfone (2020 mg/L), 100,000MWCO PVDF (1925 mg/L), and 0.3µm PVDF (1498 mg/L) membranes were also not significantly different, and were the most efficient at reducing TS in post-DAF PPW. The only significant difference was between the top performing 0.3µm PVDF membrane and the bottom performing 0.1µm Polysulfone, 100,000MWCO PVDF and the 30,000MWCO PVDF membranes. With a mean permeate TS concentration of 1498 mg/L, the 0.3µm PVDF had the highest TS concentration removal efficiency of 7%.

As with the permeate COD concentration results, the 30,000MWCO PVDF and 30,000MWCO Polysulfone membranes were not significantly different in TS reduction in post-DAF PPW, indicating again that membrane material did not influence the TS removal efficiency at the smallest nominal gap size. The same was true of the 100,000MWCO Ultrafilic and 100,000MWCO PVDF membranes which were not significantly different. Like the permeate flux results, it can be concluded from the results in Table 4.2 that, for the lowest mean TS concentrations and highest TS removal percentages, either the 0.3µm PVDF, 100,000MWCO PVDF or 0.10µm Polysulfone membrane should be selected.

TSS Concentration

The mean concentration of suspended particulates in each PPW sample for the 6 membranes was measured using TSS. The TSS values were determined by averaging TSS values from each trial after a period of one hour for the 3 repetitions. The membrane producing the lowest TSS concentrations and highest TSS removal percentages was deemed the most effective. The TSS results are summarized in Table 4.2 and graphically represented in Figure 4.7.

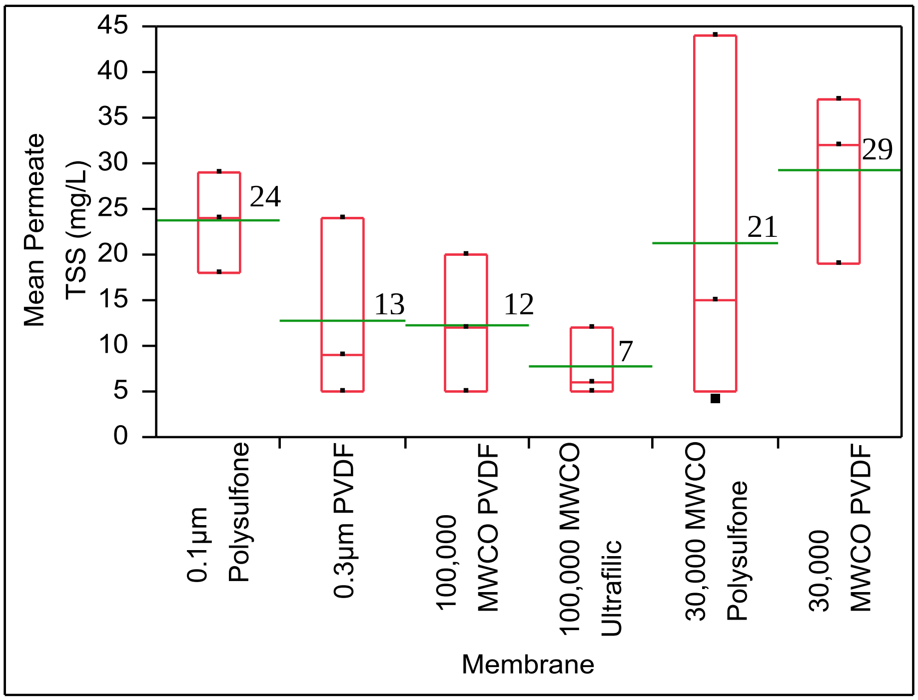

Figure 4.7. Mean permeate TSS (mg/L) for 6 membranes filtering post-DAF poultry processing wastewater for 60 min

The mean TSS concentrations (mg/L) for raw PPW and pre-sieved PPW samples for the 18 membrane filtration trials were 49 and 48 mg/L, respectively. Thus the 106µm pre-sieve reduced the TSS concentration on average by 2%. There was no significant difference (P=0.1984) in the performance of any of the membranes in terms of TSS reduction. These results indicate that TSS concentration reduction would not be a viable criterion for membrane selection.

Conclusions

The maximum mean permeate flux value of 224 $Lm^{-2}h^{-1}$ and lowest mean TS value was obtained by the 0.3µm PVDF membrane (1498 mg/L, 7%). The lowest COD concentration, and corresponding highest reduction percentage, was obtained by the 100,000MWCO Ultrafilic membrane (373 mg/L, 40%).

Using the previously described performance index (Pm_i), the most effective membrane for treatment of post-DAF PPW was determined. Based on calculated Pm_i values as shown in Table 4.3, the 100,000MWCO Ultrafilic membrane was determined to be the most effective (Pm_i = 3.56 on a 4.0 scale) in regards to maximizing permeate flux, and COD and TS reduction. Interestingly the 100,000MWCO PVDF membrane (Pm_i = 2.22) was the least effective membrane indicating that membrane material played a critical role in membrane performance at the 100,000MWCO level. The second most effective membrane was the 30,000MWCO PVDF membrane (Pm_i = 3.24), followed by the other 30,000MWCO membrane made of Polysulfone (Pm_i = 3.02) indicating that membrane material does not make a significant difference at the 30,000MWCO level in treatment of post-DAF PPW. The 0.3µm PVDF membrane (Pm_i = 2.86) placed fourth in performance index value, followed by the 0.1µm Polysulfone membrane (Pm_i = 2.40) in fifth place.

Table 4.3. Performance index values for 6 membranes treating post-DAF poultry processing wastewater based on maximum permeate flux, and reduction of COD and TS over 60 min of operation based on significant difference ($P<0.05$)

		COD	Permeate Flux	TS	Performance Index (Pm_i)
1	100,000 MWCO Ultrafilic	4	4	2	**3.56**
2	30,000 MWCO PVDF	4	3	2	**3.24**
3	30,000 MWCO Polysulfone	4	3	1	**3.02**
4	0.3µm PVDF	2	4	3	**2.86**
5	0.1µm Polysulfone	1	4	3	**2.40**
6	100,000MWCO PVDF	2	3	3	**2.22**

The permeate flux values ($Lm^{-2}h^{-1}$) calculated in this experiment can be used to determine the surface area of membrane (m^2) required to treat a known volume of PPW in a full scale membrane filtration system. As an example, a typical broiler processing plant slaughtering 250,000 birds per day (bpd) and utilizing 26 L per bird will produce 6,500,000 L of PPW. If a membrane filtration system was designed to operate 24 hours per day, then 270,833 L of PPW would need to be treated each hour. Results of this experiment showed the top performing membrane in terms of flux was the 0.3µm PVDF membrane which averaged 224 $Lm^{-2}h^{-1}$. Thus, by dividing 270,833 Lh^{-1} by 224 $Lm^{-2}h^{-1}$ it can be determined that 1209 m^2 of membrane would be needed to filter the total PPW stream. Use of the 100,000MWCO Ultrafilic membrane would require 2708 m^2 of membrane.

The experiment determined that pre-sieving of post-DAF PPW to 106µm prior to membrane filtration reduced COD by 2%, TS by 6%, and TSS by 2% making pre-screening of post-DAF PPW most likely unnecessary in preparation for membrane filtration. Membrane filtration of post-DAF PPW reduced the COD concentration by as much as 40%, and TS concentration by as much as 7%. These results indicate that membrane filtration of post-DAF PPW will be effective at reducing the organic content, but not the total solids content of post-DAF PPW.

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CHAPTER 5

CONCLUSIONS AND FUTURE DIRECTIONS

Membrane filtration has become a popular wastewater treatment method because of its ability to remove minute particles such as fats, protein and pathogens, and is now cost competitive with traditional treatment methods (Lo et al., 2005). The objectives of this study were to evaluate the effects of membrane filtration on pre- and post-DAF PPW. To accomplish this, two membrane filtration experiments were carried out as described in Chapters 3 and 4. The pre- and post-DAF PPW samples were pre-sieved to 106μm, to reduce fouling of the test membranes. Membrane filtration was carried out using the Spintek STC bench-scale system.

Conclusions

The first experiment involved membrane filtration of pre-DAF PPW with emphasis on 3 membrane pore sizes (0.30μm PVDF, 0.10μm Polysulfone and 100,000 MWCO Ultrafilic) and 2 transmembrane pressures (50 and 80psi) as main effects. The Spintek system was operated at a flow rate range of 2.4 to 3.0 L/min and pump speed range of 750 to 1000 rpm. The second experiment involved membrane filtration of post-DAF PPW with emphasis on 4 membrane pore sizes (0.3μm, 0.1μm, 100,000MWCO and 30,000MWCO) and 3 membrane materials (Polysulfone, PVDF and Ultrafilic) as main effects. The Spintek system was operated at 50 psi, at flow rate range of 2.3 to 2.6 L/min and pump speed 1207 rpm.

The concentration of organics present in the PPW was measured by using COD in Experiments 1 and 2, while solids content was determined using TS in Experiments 1 and 2, and TSS in Experiment 2. Membrane efficiency was determined by permeate flux, which was expressed in terms of $Lm^{-2}h^{-1}$. Both experiments were carried out using the same general procedures. Differences between the two experiments included statistical analysis, time of trial runs, and main effects. While the first experiment was designed as a 3x2 factorial design and thus was analyzed using a factorial analysis of variance (ANOVA) with an interaction term, the second experiment was analyzed using a one-way ANOVA since 4 membrane sizes and 3 membrane materials were utilized in a non-factorial arrangement. Trials in the first experiment were conducted for 2 hr, however results from the first experiment showed that permeate flux values generally stabilized after one hour of filtration. Thus, trials in the second experiment were conducted for 1 hr which allowed for the doubling in the number of trials conducted in a single day. Finally, the first experiment focused on the main effects of membrane pore size and transmembrane pressure. Analysis for results in experiment 1 created the question of the impact of membrane material on treatment of PPW. Thus, the second experiment focused on the main effects of membrane pore size and membrane material.

The most effective and suitable membrane for both pre-DAF and post-DAF PPW membrane filtration based on the 3 parameters of COD, permeate flux and TS was generated using weighted linear aggregation (WLA) as described by Eastman et al. (1995) and Saaty (1977). A performance index was generated to indicate which of the membranes was the most efficient for the membrane filtration of pre- and post-DAF PPW as shown in Tables 5.1 (Experiment 1) and 5.2 (Experiment 2). From these results, membrane filtration on pre-DAF PPW using 0.30µm PVDF membrane was the most suitable in terms of permeate flux, COD, and TS reduction and its performance was comparable to the existing DAF pre-treatment, whereas in post-DAF PPW pre-treatment, the 100,000MWCO Ultrafilic membrane was determined to be the most effective.

Table 5.1. Best performing membrane for treatment of pre-DAF poultry processing wastewater based on maximum permeate flux, and reduction of COD and TS over 60 min of operation based on significant difference ($P<0.05$)

		COD	**Permeate Flux**	**TS**	**Performance Index (Pm_i)**
1	0.3µm PVDF	2	3	3	**2.54**
2	100,000 MWCO Ultrafilic	2	3	2	**2.32**
3	0.1µm Polysulfone	1	2	1	**1.32**

Table 5.2. Performance index values for 6 membranes treating post-DAF poultry processing wastewater based on maximum permeate flux, and reduction of COD and TS over 60 min of operation based on significant difference ($P<0.05$)

		COD	**Permeate Flux**	**TS**	**Performance Index (Pm_i)**
1	100,000 MWCO Ultrafilic	4	4	2	**3.56**
2	30,000 MWCO PVDF	4	3	2	**3.24**
3	30,000 MWCO Polysulfone	4	3	1	**3.02**
4	0.3µm PVDF	2	4	3	**2.86**
5	0.1µm Polysulfone	1	4	3	**2.40**
6	100,000MWCO PVDF	2	3	3	**2.22**

Permeate flux ($Lm^{-2}h^{-1}$) was used to determine effluent flow efficacy. Logically, as the concentration of a PPW sample decreases, permeate flux increases. This can be seen in the results of the 2 experiments. When the 0.3µm PVDF membrane was utilized to treat the higher concentration pre-DAF PPW, an average permeate flux of 115 $Lm^{-2}h^{-1}$ was achieved. Conversely, when the same 0.3µm PVDF membrane was used to treat the less concentrated post-DAF PPW, an average permeate flux of 224 $Lm^{-2}h^{-1}$ was achieved, which represented a 95% increase in the effluent flow rate.

Permeate flux results from the two experiments can be used to determine the square meters (m^2) of membrane that would be required by a full-scale PPW treatment systems at the poultry processing plant, in that the mean permeate flux plays an essential role in the calculation of the required membrane surface area. For example, using a typical poultry processing plant that slaughters 250,000 birds per day (bpd) and uses the average 26 L of portable water per bird (Lpb), it can be calculated that such a plant would generate 6.5 million L of PPW per day. The assumption is also made that an automated membrane filtration system operating 24 hr a day is utilized. In the Conclusion section of Experiment 1 (Chapter 3), it was calculated that 2355 m^2 of the top flux producing 0.3µm PVDF membrane would be required to treat 6.5 million L of pre-DAF PPW. In comparison, the Conclusion section of Experiment 2 (Chapter 4) reports that only 1209 m^2 of 0.3µm PVDF membrane would be required to treat 6.5 million L of post-DAF PPW, effectively reducing the required surface area of membrane by 49%. From the above deductions, a post-DAF PPW on-site treatment system less would require approximately half the membrane surface area required for treatment of a pre-DAF PPW stream of the same volume. Thus from an initial capital investment standpoint, membrane filtration of post-DAF PPW would be preferable over pre-DAF PPW. However, because chemical addition plays a critical role in DAF treatment, the operating cost savings of reducing chemical demand in DAF systems by employing pre-DAF PPW membrane filtration could play a substantial economic role.

Future directions

Future research in membrane filtration of PPW should consider exploring the use of membrane (materials and pore sizes) combinations in treating PPW. Further analytics should be done to look at membrane filtration effectiveness on other critical wastewater parameters such as TKN and other nutrients. In addition, future experiments should explore the potential for maximizing pre-screening (e.g., tertiary microscreening) prior to membrane filtration of PPW. The ability of membrane filtration to reduce pathogens (e.g., bacteria) should be further studied. Exploring the different membrane cleaning processes in membrane filtration that works best on pre- and post-DAF PPW will help in better filtration. The life cycle assessment (LCA) of pre- and post-poultry processing wastewater membrane filtration unit in an operating plant should be addressed.

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