Nutrients recovery of source separated urine by forward osmosis and a pilot scale resources-oriented sanitation system

XU Yangyu, ZHOU Lu* and JIA Qibo

School of Environment, Tsinghua University, Chenfu Road, Haidian District, Beijing 100084, PR China
(E-mail: *xu-yy14@mails.tsinghua.edu.cn; zhoulu@tsinghua.edu.cn; jiaqibo@mail.tsinghua.edu*)
*Corresponding author: *zhoulu@tsinghua.edu.cn, Tel.:+86+10+62773079*

Abstract
Urine contains large amount of nutrients and can be used as fertilizer but is difficult to be treated in sewage. To achieve the resource recovery, the new toilet system using forward osmosis (FO) as the key unit is developed. In the system, FO process is used for the concentration of urine and pre-treatment for RO. In this study, the influence of membrane materials, draw solution concentration, flow rate etc. are studied for application of FO process in urine concentration. The concentration effects of synthetic urine and real urine are compared and analyzed. With pH adjustment of urine, the rejection of N, P, K and other nutrients is more than 80%. The results show high potential of adopting FO process to recover the nutrients in urine and be used as fertilizer. Integrated with other techniques, the toilet waste water will no longer be a trouble but a resource centre.

Keywords
Forward Osmosis; Source Separation; Resource Recovery; Sanitation System.

INTRODUCTION

The toilet wastewater is the main source of municipal sewage pollutants. The commonly used end-of-pipe systems cost large amount of lands, energy, and water, the operation and maintenance expenses are very high (Balkema, 2002). On another hand, the human excreta contain large amount of nutrients such as N, P, K, which are crucial for the growth of plants, but are costly to eliminate in wastewater (Zhang, 2014). Alternative toilet systems are developed, such as eco-sanitation system. These systems use different methods and techniques to achieve the close-loop cycle of water and nutrients (Chen, 2013).

Forward Osmosis (FO) is a green membrane technology using the osmotic pressure differentials between the feed and the draw as the driven force to concentrate the feed solution. And this technology has drawn growing attention in recent years because of the following characters（Cath, 2006; Lutchmiah, 2014; Xue, 2016）:

1. No need for external high pressure compared with other membrane processes;
2. Low fouling intensities and easy recovery after fouling due to the low hydraulic pressure;
3. The strength requirements for membranes are lower;
4. Energy saving if the draw solution (DS) recovery is not considered.

Due to the characteristics of FO, it can be used to enrich solutions with high concentrations and pollutants. Source separated urine contains high concentration of nutrients and some organics, and is always difficult to be eliminated when it gets into the sewage. Therefore, some researchers have studied the possibility of adopting FO for urine treatment. And their results showed some drawbacks: low water flux due to the high concentration of urine; low rejection for nitrogen; draw solution contamination, etc. (Zhang, 2014; Xue, 2015; Liu, 2016). Moreover, most of the studies used synthetic urine with small scale in the lab which can be different from the practical situation. In this study, the methods to improve the efficiency of urine concentration by FO process are studied as well as the comparison between synthetic urine and real urine.

Furthermore, a pilot scale sanitation system using FO as the key unit is built to testify the effect of FO. This toilet system adopts the urine-diversion vacuum toilet. After separately collected, the urine with the flushing water is concentrated by FO followed with the reverse osmosis (RO) to recover the draw solution in the FO process. After concentration, the volume of urine is dramatically reduced, the enriched urine is convenient for transportation and used as a liquid fertilizer. The faeces are digested to eliminate the pathogens.

METHOD AND MATERALS

1.Experimental set-up

The diagram for FO experiment is shown in **Figure 1(a)**. The experiment platform consists of flat sheet FO membrane module, peristaltic pump, flow meter, containers of feed solution (FS) and draw solution (DS), tubes, electronic scales (Napco, JA31002）, conductivity meter (WTW, multi 3420), data acquisition PC. The liquid and its velocity is driven and controlled by the pump. The water flux can be calculated from the weight incremental of DS which is measured by the scale and recorded by the PC. The conductivity meter takes records of the conductivity of liquids. **Figure 1(b)** shows the module design of the FO chamber, the effective contact area is 0.023 m^2. Experiments are conducted intermittently, each time running for 4 hours under room temperature with the FO mode (Feed facing the active layer). The cross velocity is controlled by the pump.

2.Materials

Membrane: The FO membranes used in the experiment are CTA-NW and TFC membranes (HTI), AQP membranes (FO AIM4010, Aquaporin), RO membrane (FELMETIC SW30, DOW). Besides, the RO membrane is modified by eliminating the supporting layer. All membranes are soaked in the methane for 2h before experiment.

Feed solution: The feed solution concludes synthetic urine and real urine taken from a public toilet. The recipe of synthetic urine refers to Wignarajah K's recipe (Wignarajah K, 2006).

Draw solution: Considering the possibility for recovery using reverse osmosis, the draw solution in the experiment is 0.5-2.0 mol/L NaCl.

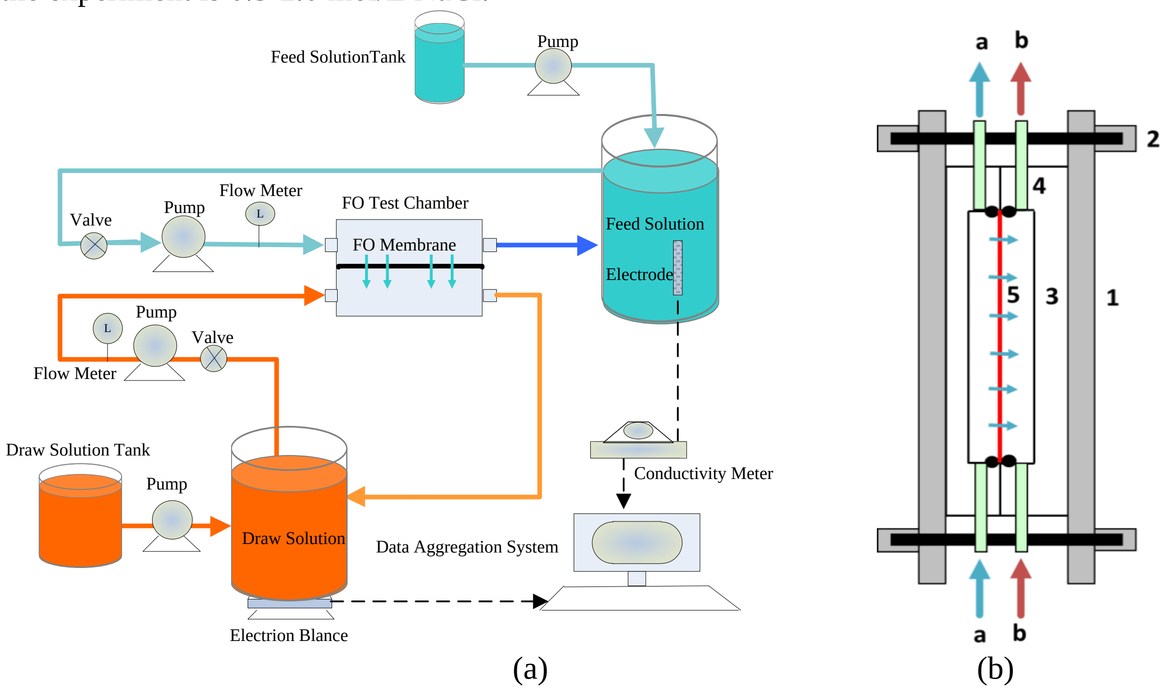


Figure 1. Experimental set-up for FO system and FO module

(1: fixed splint; 2: strap bolt; 3: flat water channel; 4: draft tube; 5: FO membrane. a: FS; b: DS）

3.Data collection and analysis

The weight loss or volume change of the feed is measured to calculate the water permeation of the membrane. And the feed samples are taken before and after concentrated by the FO process, the

ions and nutrients content are analysed. The ions concentrations are measured by IC (Dionex, ICS 2000), TN, TP, NH_3-N are measured by *Alkaline potassium persulfate digestion UV spectrophotometric*, *Ammonium molybdate spectrophotometric* and *nessler's reagents spectrophotometer*. The scanning electron microscopy (SEM) was used to observe the surface and cross-section of FO membrane.
The water flux is calculated by equation (1).

$$J_w=\Delta w/(\rho st) \tag{1}$$

In equation (1), Δw：weight incremental of DS（kg）；ρ：density of liquid（kg·L^{-1}）；s：effective area of membrane（m^2）；t：time interval（h）
The rejection of nutrients in feed is calculated by equation (2):

$$R_f = 1-\frac{C_p}{C_f} \tag{2}$$

In equation (2), C_f：concentration of the feed（mol·L^{-1}）；C_p：concentration of the permeate（mol·L^{-1}）.

RESULTS AND DISCUSSION

1. Performance comparisons of different membranes

The comparison of water flux and rejection of different membranes can be seen in **Figure 2**. The membrane features are tested using 1.0 M NaCl as draw solution and deionized water as feed solution.

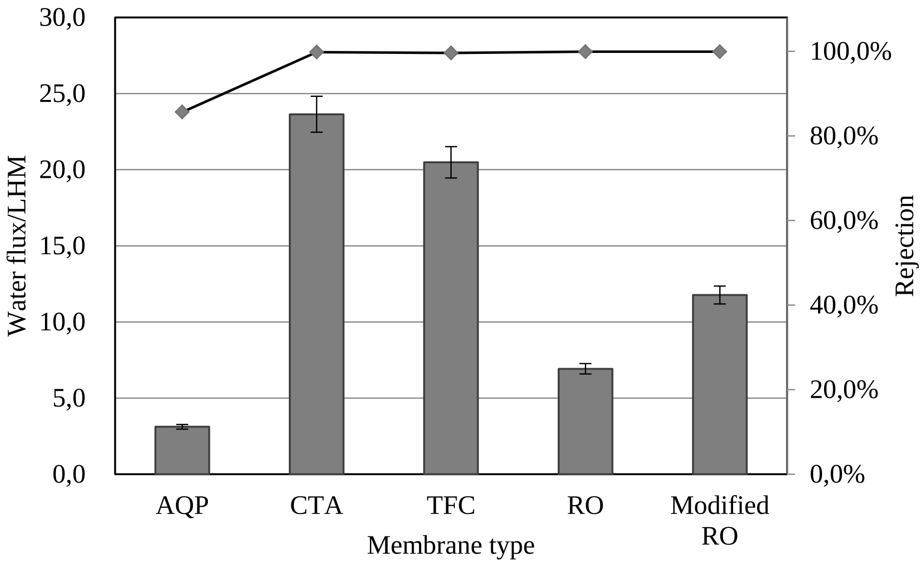


Figure 2. Water flux and rejection of different membranes

The CTA, TFC membrane shows the best performance with water flux of 23.6 LHM and 20.5 LHM, rejection of 99.8% and 99.6% respectively. The RO membranes show slightly higher rejection, but the water flux is only 1/3 of CTA membrane. Besides, the modification of the RO membrane contributes to the increase in water flux mainly due to the decrease of concentration polarization. This improvement provides possibility of adopting RO membrane in FO process by membrane modification.

2.Influence of draw solution concentration

A range of different concentrations of NaCl are used to find out the most suitable concentration for practical use. The influence of draw solution concentration on water flux is shown in **Figure 3**.

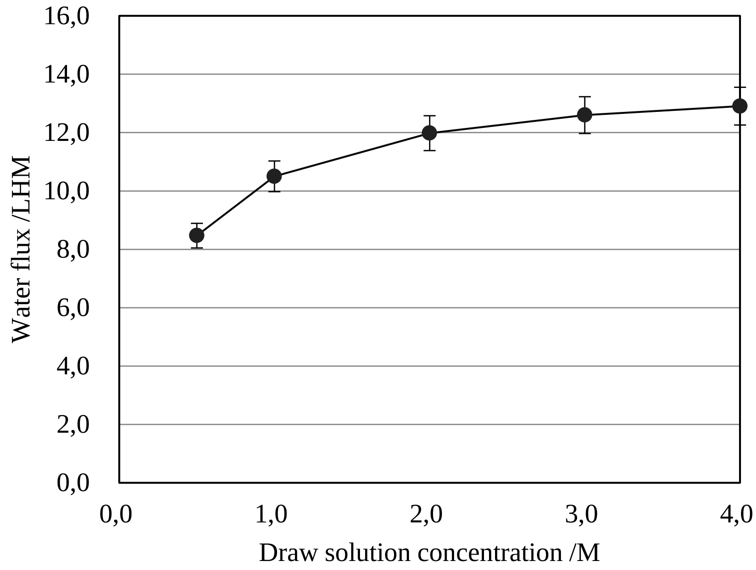


Figure 3. Influence of draw solution concentration on water flux.

As in **Figure 3**. the water flux increases as the draw solution concentration goes up. The increasing rate declines. Due to the limitation of the pump pressure and energy consumption of reverse osmosis for draw solution recovery, we use 2.0M NaCl solution as the draw initially (Xu, 2010). As the FO process goes on the concentration of draw solution goes down to 1.0-1.5M.

3.Influence of cross velocity

The influence of the cross velocity on water flux is shown in **Figure 4**. Cross velocity mainly affects the external concentration polarization (ECP) besides membranes, and higher velocity has a positive effect on the decrease of membrane fouling because of the physical washing (McCutcheon, 2008). However, the increasing rate of water flux decreases when the flow rate increases which may due to the change of flow state (Kim, 2012).

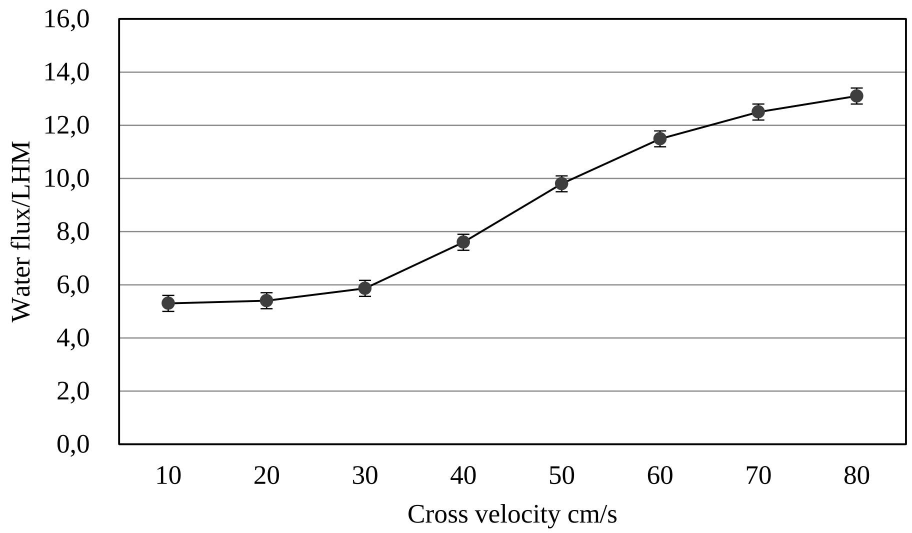


Figure 4. Influence of water flow rate on flux.

4.Concentration effect using synthetic and real urine

The concentration effect for synthetic and real urine of FO process is listed in **Table 1**. The CTA membrane is used to conduct the urine concentration experiment; the draw solution is 1M NaCl. The urine is concentrated for 2 times (volume reduced to 1/2 after concentration). The FO membrane has a high rejection for P, and a relatively low rejection for organics and K. The rejection for nitrogen is the lowest.

Table 1. Nutrients concentration of urine before and after FO process.

Urine type		TP (mg/L)	TN (mg/L)	NH_3-N (mg/L)	COD_{Cr} (mg/L)	K (mg/L)
Synthetic urine	Before	3210±5	12550±5	12440±5	4550±5	840±5
	After	6240±5	16950±5	16370±5	7630±5	1480±5
	Rejection	97.2%	73.4%	65.8%	83.9%	88.1%
Real urine	Before	2110±5	2460±5	2350±5	4030±5	575±5
	After	4140±5	3160±5	2570±5	6960±5	970±5
	Rejection	97.9%	64.5%	54.7%	86.3%	84.1%

The most important principal for the rejection of membrane is the molecular screen effect and the charge effect (Striemer,2007). For this reason, the low rejection for nitrogen may due to the small molecule size and its low charge state. And the most of the nitrogen exist as ammonia, which is similar to the H_2O molecule, leads to the unsatisfying rejection for nitrogen.

Moreover, the application in real urine comparing to synthetic urine, the rejection is similar. However, the nutrients concentration of real urine is much lower than that of synthetic urine, which causes another trouble for fertilizer effect. To promote the fertilizer efficiency, the real urine needs to be concentrated more, which will lead to longer processing time and more energy consumption.

5.Influence of pH on nutrients rejection

To improve the rejection for nutrients, adjustment can be adopted in membrane or the feed. In this study, the pH value of the feed is adjusted to promote the rejection for nitrogen. The nitrogen rejection under different pH value is shown in **Figure 5**.

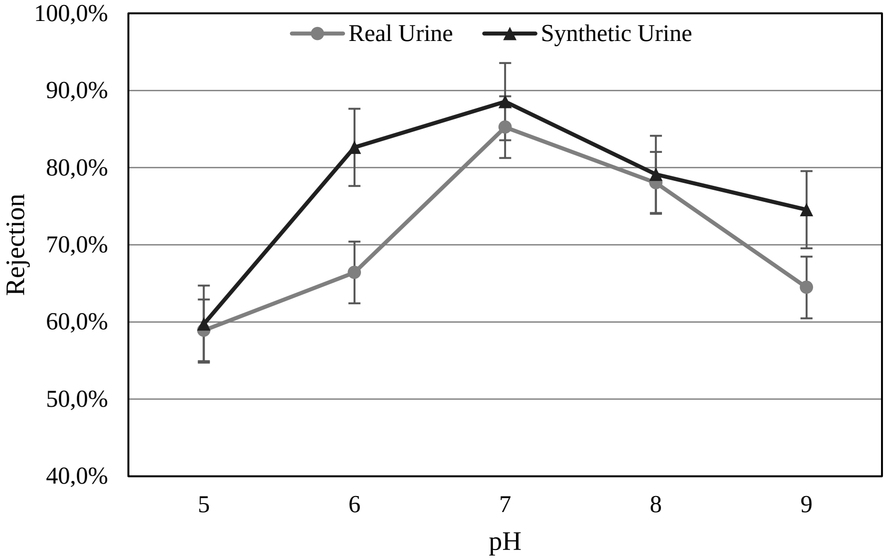
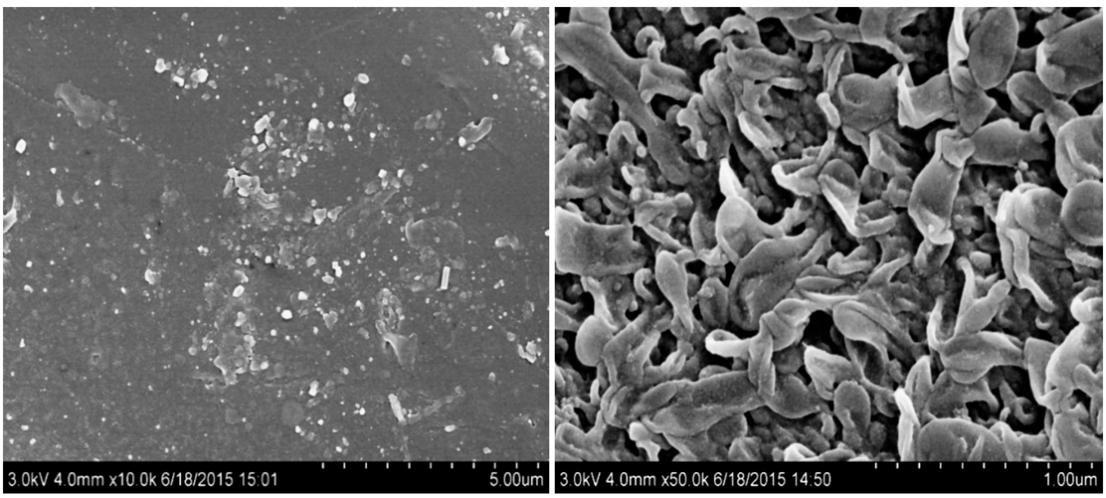


Figure 5. Influence of pH on nitrogen rejection

The highest rejection is achieved at pH=7 in both synthetic urine and real urine. When pH=7, ammonia mainly exists as NH_4^+-N, and the permeability of the membrane is not influenced by the pH, under this circumstance, the combined result of molecular screen effect and the charge effect achieved the best rejection for nitrogen (Cath&Gormly, 2005; Cath&Adams, 2005). When pH is lower the permeability of the membrane increases thus allow more ammonia molecules to get through. Meanwhile, the durability of the membrane will be affected (Bellona, 2004).

6.Membrane fouling

After operation for 1 month, the SEM of the membrane was taken to investigate the membrane fouling condition. As in **Figure 6(a)**, some pollutants can be seen on the surface, they clustered as irregular crystals. But when magnified the picture as in **Figure 6(b)**, the inner space of the membrane stays clean.



(a) (b)

Figure 6 SEM of the used membrane

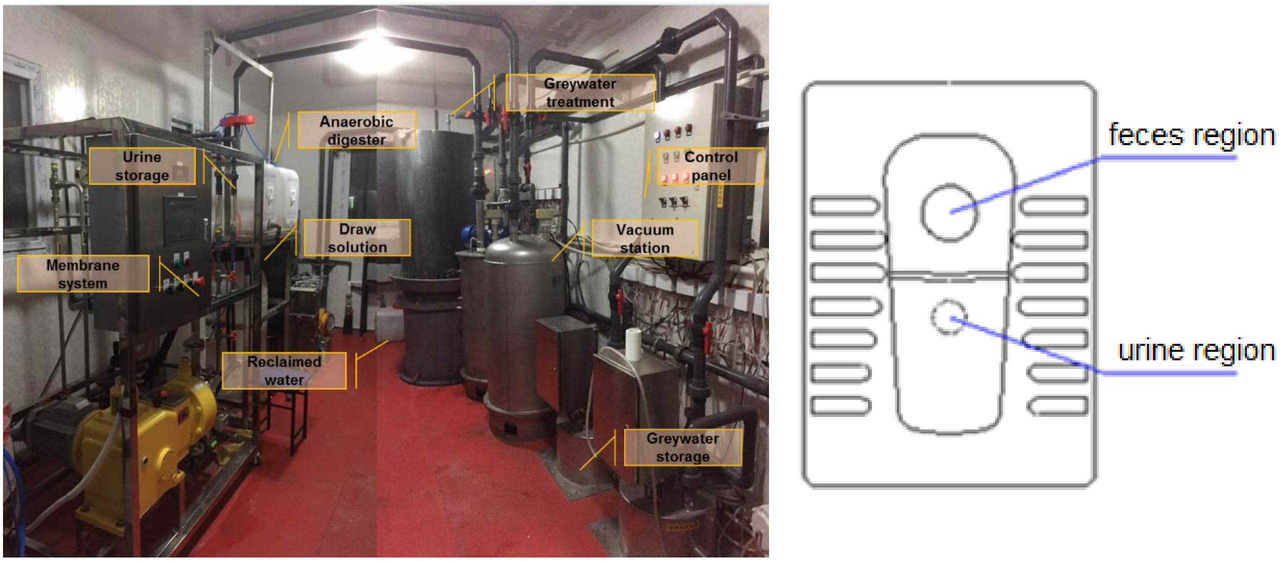
This phenomenon means the pollutants just adhere to the surface; they can be easily cleaned out by simple physical back wash. And it indicates the FO process behaves well on the aspect of membrane fouling (Lee, 2010; Mi, 2010).

7.Operational results of pilot scale onsite project

System introduction

The pilot scale toilet and its resource recovery system was deployed at the northwest corner of the playground of Tsinghua University Primary School. The system consists a 6 squatting positions toilet and a treatment system, and is designed to have the capacity of 100 users per day.

Water-saving source separated vacuum toilets and urinals are adopted in the system, which have significant efficiency of flushing, consuming only 1L and 0.1L water per flush for urine and faeces. The toilets and urinals and its collecting system—vacuum station are provided by *EnviroSystems Engineering & Technology Co., Ltd.* The human excreta are collected separately through the special design of the stool, which is divided in to 2 parts, the former is the collecting bowl for urine, and the latter is for faeces. The layout of the toilet wastewater treatment system is shown in **Figure 7(a)**, and the principal of the urine diversion toilet is shown in **Figure 7(b)**.



(a) **(b)**

Figure 7 The pilot scale toilet wastewater treatment system and the urine diversion toilet

The RO membrane is used to reduce the cost of the FO module. The module is designed as flat sheet with a dimension of 20cm×60cm, with an effective area of 0.075m^2 each membrane. 100 membranes are put together with mesh spacers separations (Zhang H, 2014).

Operational results

The collected urine is diluted about 1.3-1.5 times by the flushing water (0.1L of flushing water and 0.2-0.3L urine), and after the FO process the urine can be enriched for 2.5 times, the volume is reduced enormously, and the concentration of nutrients increases and can be used as a liquid fertilizer.

The reclaimed water is produced from urine, after pre-treatment by FO, the RO process produces a real high quality reclaimed water for reuse of toilet flushing and greening.

CONCLUSIONS

In this study, the influence of membrane materials, draw solution concentration, flow rate etc. are studied for application of FO process in urine concentration. The results showed high potential to use FO process to recover the nutrients in urine and used as fertilizer. Integrated with other techniques, the toilet waste water will no longer be a trouble but a resource centre.
With adjustment in pH of the urine, the rejection for N, P, K and other nutrients in urine can be rejected to more than 80%, the nutrients concentration rises along with the reduction in urine volume.
The system produced high quality fertilizer without additional input of water and other substances. The installation process doesn't need much reformation of the location, and the whole system runs on the excreta produced by people. The system can be integrated and manufactured as modules, and used under circumstances such as: sightseeing places, parks, islands, and other places where municipal pipelines are unavailable. Therefore, the toilet system has a high potential for the market.

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