Nanofiltration for Safe Drinking Water in Underdeveloped Regions – A Feasibility Study

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Abstract
The fact from the United Nations that in 2015, about 663 million people worldwide did not have access to an improved drinking water source, does not resemble the reality wherein more than 1.8 billion people worldwide were consuming water which is unsafe for drinking. Nanofiltration, with the ability to reject several trace organic compounds, heavy metals and viruses at a lower energy demand than reverse osmosis, has found application for the production of high quality drinking water in developed nations. This study briefly reviewed the efficacy of nanofiltration for drinking water production considering various types of pollutants. Series of experiments were conducted using a pilot-scale nanofiltration unit, to assess the potential for drinking water production, from ground water, in a developing country like Ghana and to estimate the associated costs. The economic feasibility of a micro-enterprise (relying on nanofiltration) was evaluated for tackling the economic water scarcity in a rural area. The concept of micro-enterprise based on a pilot-scale nanofiltration system was found to be suitable for producing adequate quantity of safe drinking water (at a reasonable cost of less than €0.01 per litre) for a village in a developing country. Offering safe and economic drinking water with a possibility for small margins and employment opportunities aiming for poverty alleviation, its operation was found to be economical and sustainable.

Keywords
Developing country; high quality drinking water; micro-enterprise; nanofiltration; pilot-scale

INTRODUCTION

To "Halve, by 2015, the proportion of the population without sustainable access to safe drinking water and basic sanitation" was the among the targets of the United Nations (UN) Millennium Development Goal (MDG) - 'Ensure environmental sustainability' (United Nations, 2015). The MDG target was achieved in 2010, wherein 88% of the total global population had access to an improved drinking water source compared to 76% in the year 1990 (UNICEF & WHO, 2015). The World Health Organisation (WHO)/United Nations Children's Emergency Fund (UNICEF) Joint Monitoring Programme for Water Supply and Sanitation (JMP) monitored the progress towards this target. It had used the 'use of an improved drinking water source' as the indicator, due to the non-availability of "nationally representative data on the safety of drinking water for the majority of countries" (UNICEF & WHO, 2015). The emphasis of an improved drinking water source (like public taps, boreholes, protected dug wells, piped water supply, etc.) relies on the likelihood that it could be in general free from faecal contamination compared to an unimproved source, which however is not universal (Bain et al., 2014b). Several other studies (Bain et al., 2012; Clasen, 2010; Godfrey et al., 2011; Payen, 2011; WHO & UNICEF, 2012) also report that in many cases an improved drinking water source (including piped water supply) suffers from faecal contamination, especially in developing countries. According to UNICEF & WHO (2015) about 663 million people were still using unimproved drinking water sources in 2015. This however is an underestimation and more than 1.8 billion people worldwide use unsafe drinking water (Bain et al., 2014a; Onda, LoBuglio, et al., 2012; Payen, 2011). And this number will increase further if chemical pollutants are accounted (Godfrey et al., 2011) and becomes nearly 4 billion if the difficulty, risk and cost for access to water are considered (Payen, 2011). Poor people in developing countries pay a large portion of their meagre daily wages (see Figure 1) to gain access to an improved/safe water source (like water tanker, street seller, etc.).

Centralised approach cannot solve this water crisis in developing countries and membrane technologies are becoming preferred and plausible among the decentralised solutions (Arnal et al., 2010; Cherunya et al., 2015; Huttinger et al., 2015; Peter-Varbanets et al., 2009; Peter-Varbanets, et al., 2012; Sima and Elimelech, 2013). Ultrafiltration (UF) has been widely studied for the production of bacteriologically safe drinking water in developing countries. However, it is also known that viruses and some bacteria can permeate an UF membrane (Arkhangelsky and Gitis, 2008), for which reason some studies recommend a post-chlorination step (Arnal, et al., 2010; Huttinger et al., 2015). Furthermore, ultrafiltration fails to reject dissolved organics (insecticides, pesticides, humic substances, etc.) and heavy metals. On the other hand, several research works (Afonso et al., 2004; Peter-Varbanets et al., 2009; Sima and Elimelech, 2013) have investigated the reclamation of brackish water or sea water using reverse osmosis (RO) for the developing world scenario. Nanofiltration (NF) is a fascinating technology, lying between the boundaries of UF and RO, with better rejection capacities than UF and lower energy requirement than RO. Hardly any study exists evaluating the suitability of nanofiltration for drinking water production in developing regions, which is expected to become a promising technology (Hillie and Hlophe, 2007).

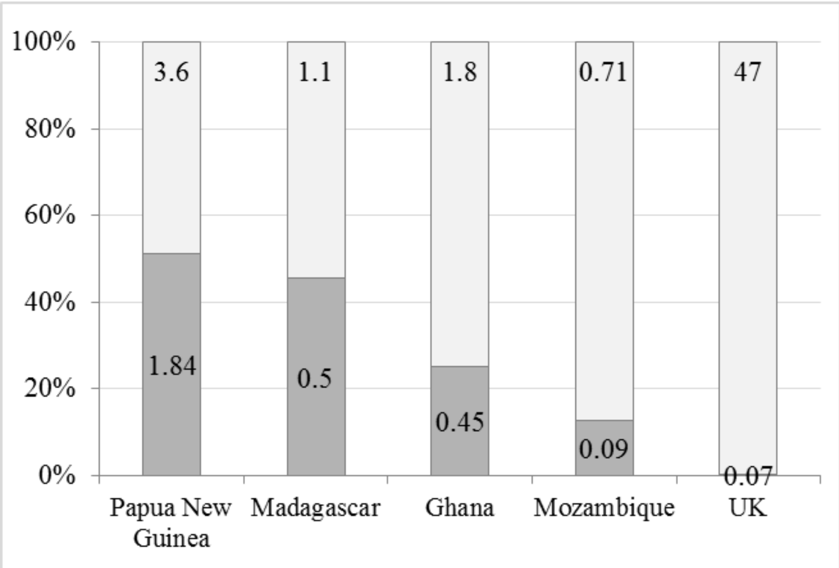


Figure 1. Typical low daily salary (in GBP) and the cost for 50L improved/safe water (in GBP) in some countries [adapted from WaterAid (2016a)]

This study evaluates the feasibility of establishing micro-enterprises using nanofiltration as means for producing safe and economic drinking water locally in developing regions. This paper will review the efficacies of nanofiltration for drinking water production, present the results from nanofiltration trials conducted at the Institute of Wastewater Management and Water Protection and evaluate the micro-enterprise concept.

NANOFILTRATION FOR DRINKING WATER PRODUCTION

The demand for water is increasing worldwide with water resources becoming scarce, besides the increasing global concern for micro-pollutants in the raw water sources for drinking water production. Over the last two decades, nanofiltration has become popular and attractive for drinking water production (see Table 1) in industrialised countries, since it can effectively remove these pollutants present at very low concentrations in a single step and without the need for addition of any secondary chemicals.

From the various studies reviewed in Table 1, it can be concluded that nanofiltration, compared to conventional drinking water treatment (DWT) and ultrafiltration, is a promising technology for producing high quality and safe drinking water free from heavy metals, micro-pollutants and pathogens at lower capital and operational costs compared to reverse osmosis. Van der Bruggen et al. (2001) and Costa and de Pinho (2006) estimated the cost of clean water produced using NF to be about €0.2/m^3 for a plant capacity of about 2000m^3/d.

Table 1. Application of nanofiltration for the production of high quality drinking water – a review

Pollutant / [Sources]	Findings
Bacter-, fung-, herb- and pesticides. [Van der Bruggen et al., 2001; Košutić et al., 2005; Ogutverici et al., 2016; Pang et al., 2010; Saitúa et al., 2012; Sanches et al., 2012]	Several NF membranes can remove many of these compounds effectively. To pinpoint some, rejection percentages up to 95, 94 and 92.5% have been reported for triclosan, dichlorodiphenyltrichloroethane and glyphosate by Ogutverici et al. (2016), Pang et al. (2010) and Saitúa et al. (2012) respectively.
Emerging micro-pollutants (pharmaceutical residues, hormones, endocrine disruptors, etc.) and pathogens. [Lopes et al., 2013; Radjenović, et al., 2008; Sanches et al., 2012; García-Vaquero et al., 2014; Yoon et al., 2007]	Studies (including full scale in DWT plants) confirm that a wide spectrum of emerging pollutants can be retained by NF, better than conventional treatment powered with activated carbon adsorption. Depending on the membrane properties and the chemical characteristics of individual compounds, the rejection capacities can range from about 30% to almost 100%.
Harmful monovalent anions (nitrate, fluoride) [Van der Bruggen et al., 2001; Garcia et al., 2006; Shen and Schäfer, 2015]	Some NF membranes can effectively reject nitrate as well as fluoride ions. The main criteria for membrane selection would be the pore diameter, besides the surface charge of the membrane.
Heavy metal ions (As, Ni, Pb, U, etc.). [Harisha et al., 2010; Košutić et al., 2005; Maher et al., 2014; Favre-Réguillon et al., 2008]	Numerous studies (lab and pilot scale) report the ability of NF to reject heavy metals from drinking water. Harisha et al. (2010) and Košutić et al. (2005) report rejection% of more than 85% for As using NF, which is not much different from the rejection capacity of RO.
Natural organic matter. [Costa and de Pinho, 2006; Ericsson et al., 1997]	Almost all NF membranes can remove humic substances effectively without compromising on permeate flux unlike RO membranes.

In developing countries, rapid industrial growth with low environmental concern and lack of strict regulation results in serious pollution of its water resources. Even the ground water in such countries can be expected be more polluted than in the industrialised countries with strict regulations. For these scenarios, nanofiltration could possibly be used to produce safe drinking water at reasonable costs.

NANOFILTRATION TRIALS FOR ESTIMATION OF POTENTIAL

Ghana was chosen as a reference country for this study as: it is among the countries with economic water scarcity (UNESCO, 2012), several organisations and NGOs have been working in its rural areas (like Safe Water Network, Water.org, WaterAid) and the due to the availability of ample scientific literature.

Materials & Methods

Since the surface waters in Ghana are mostly highly polluted (Abdul-Razak et al., 2009; Danquah et al., 2011; Karikari and Ansa-Asare, 2006); for this study, ground water was chosen to be the raw water source. Model ground water [based on the average of values reported by Tay and Kortatsi (2008)], with a composition as in Table 2, was prepared using deionised water, inorganic salts and sodium salt of humic acid (45-65% humic acid (HA) content, purchased from Carl Roth GmbH, Germany). Membrane cleaning was carried out using solutions of sodium hydroxide and hydrochloric acid. All chemicals used were of analytical grade.

Table 2. Composition of model ground water [adapted from Tay and Kortatsi (2008)]

Parameter	(mg/l)	Parameter	(mg/l)	Parameter	(-)
Calcium	23.2	Chloride	64.3	pH	7.1
Magnesium	12.2	Nitrate	10.3	Turbidity (NTU)	1.5
Sodium	37.3	Iron	0.004	Colour No. (m^{-1})	14
Potassium	3.3	Manganese	0.007	Conductivity (μS/cm)	275
Bicarbonate	116	TOC*	15.4		

* A high value was chosen by authors, as nominal values could not be obtained from literature

A schematic of the pilot scale nanofiltration unit is shown in Figure 2. Effluent treatment (ET)-System [more details of the system can be found elsewhere, ROCHEM (2008)] comprising of disk tube (DT) module packed with DOW NF270 membrane (active surface area of 1m^2) was provided by RTS Rochem Technical Services GmbH, Germany. The system has a rotary vane pump (coupled to a 230 V, 750 W motor) capable of providing a flow rate of about 800 L/h over a range of pressure from 3 to 9 bar (g). All experiments were performed at 14 ± 0.2^{o}C.

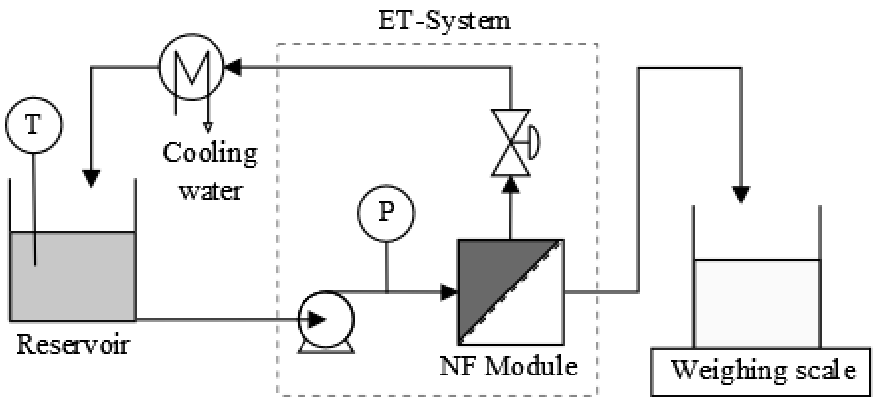


Figure 2. Schematic of the nanofiltration setup used in the study

Two types of experiments were conducted to evaluate the water production capacity of the unit and to study the fouling tendencies. In the first set of experiments (totalling 7 trials), feed water (initial volume of 120 L) was concentrated up to 9 times at 7 bar pressure and the permeate was collected in a container placed on a weighing scale. The weight of the permeate collected over time was recorded and was used to calculate the temperature-corrected permeate flux. At the end of each experiment, samples of concentrate and compounded permeate were collected and their pH, conductivity and TOC content were measured. The collected permeate from permeate reservoir was given back to the feed reservoir and mixed well before starting the new batch. After the 7 trials, the membrane was subjected to chemical cleaning using NaOH (0.1%) and HCl (0.2%) solutions. In the latter part of the study, filtration was carried out at 5 bar and both retentate & permeate were given back into the reservoir. The setup was run continuously for 28 days and the volume flow rate of permeate was measured regularly to determine the flux.

Conductivity and pH of the collected retentate and permeate samples were measured using GLF100 conductivity meter (Greisinger electronic GmbH, Germany) and Multi HQ40D device (Hach Lange GmbH, Germany). Total organic carbon (TOC) and nitrate concentration in the samples were determined using Multi N/C 3000 analyser (Analytik Jena AG, Germany) and V-550 UV/vis spectrophotometer (JASCO Labor- und Datentechnik GmbH, Germany) respectively following the German standard methods (GDCh & DIN, 2016).

Results & Discussion

The measured permeate flux from the seven consecutive batches (without membrane cleaning) can be seen in Figures 3 and 4a. The initial rapid decline in flux during first batch (see Figure 4a) should be attributed to compaction of the membrane (which was permitted before extracting permeate in subsequent trials) and then some degree of fouling. There was hardly any difference in the initial permeate flux or the trend during filtration in trials after first batch. This suggests that the fouling

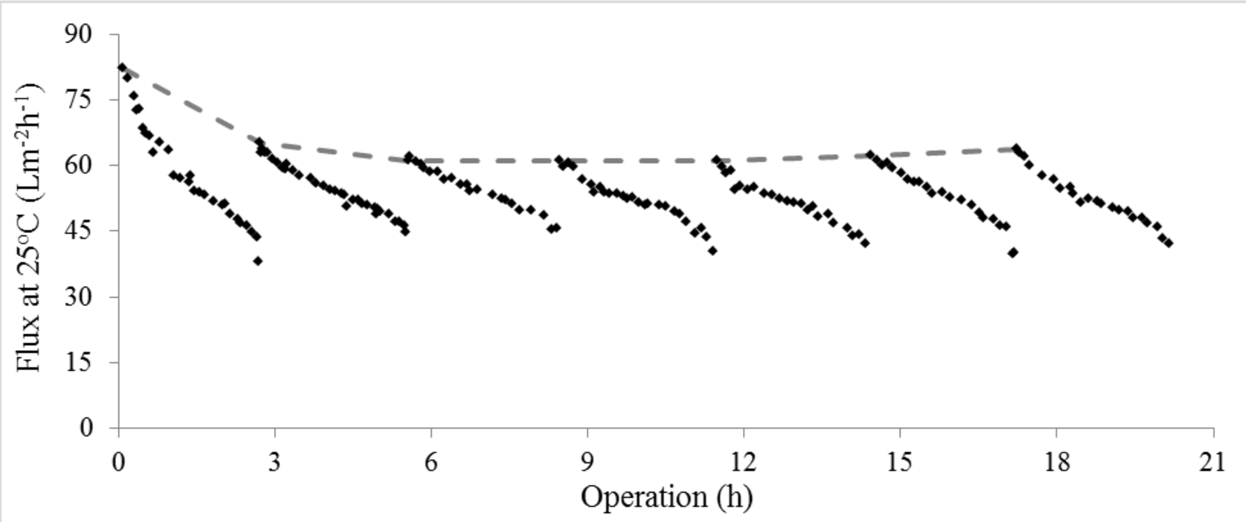
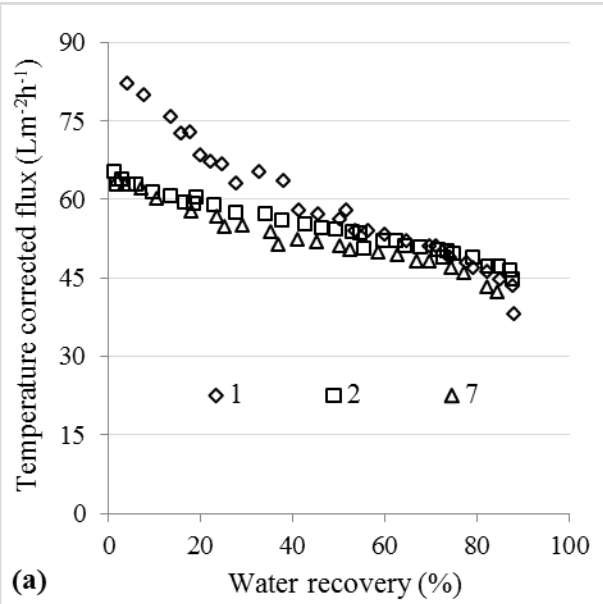


Figure 3. Change of permeate flux during nanofiltration cycles (WCF≈0.88) – 7 operation cycles without membrane cleaning



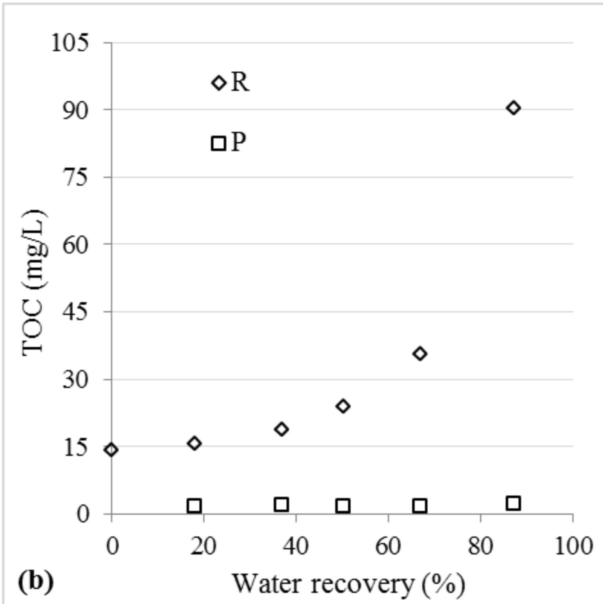


Figure 4. (a) Comparison of permeate flux from 1st, 2nd and 7th trials; (b) TOC content in retentate (R) and permeate (P) during concentration of model ground water – from trial 7

layer did not grow further and that the module could be used for longer durations without the need for cleaning. A flux decline of about 25% was to be seen during each batch due to the increase in osmotic pressure resulting from concentration of feed water.

Water permeability with the feed model ground water (9-10 $Lm^{-2}h^{-1}bar^{-1}$) was only slightly lower than the measured clean water permeability of about 11 $Lm^{-2}h^{-1}bar^{-1}$. Figures 4b and 5a show the rejection efficacy of the membrane for organics and figure 5b shows the retention of total dissolved solids (TDS) expressed in terms of conductivity. It is well known from various studies and from the membrane datasheet from Dow Filmtec, that NF270 offers high water fluxes, high and low to high rejections for organic and inorganic (depending on hydrated size and valency of the ion) solutes respectively. At 88% water recovery, all permeate samples had less than 2 mg TOC/L and their conductivity ranged from 140-170 µS/cm. pH value of all samples was measured to be within the range of 7.2-8.2. NF270 does not have the ability to reject nitrate ions (also observed in this study, data not shown). Should the raw water source contain high nitrate concentration (> 50 mg/L), an appropriate membrane (for e.g. NF70 or NF90) must be selected.

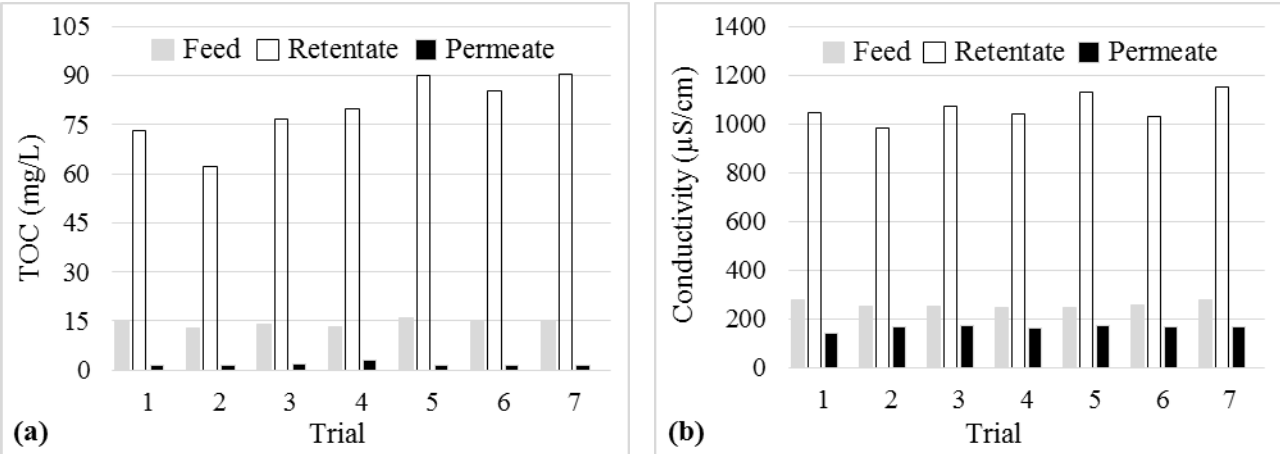


Figure 5. Rejection of TOC and TDS during 7 consecutive trials (water recovery = 88%)

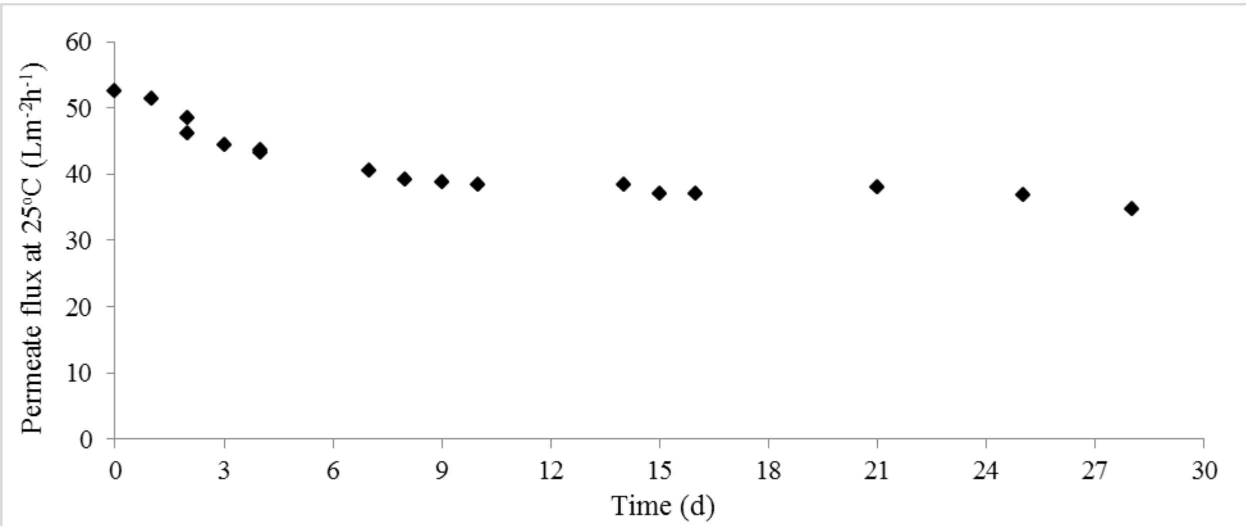
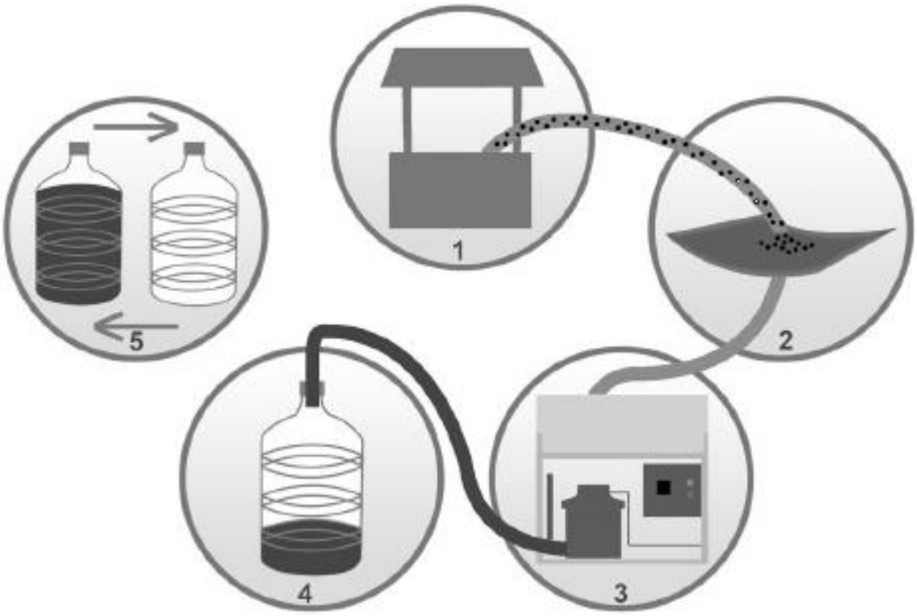


Figure 6. Decline in permeate flux during the fouling experiment at 5 bar

Figure 6 shows the decline in water flux (about 29% in 28 days) during the long-term fouling experiment. A slight reduction in feed TOC was observed during this period (likely due to fouling), however, the permeate TOC was about 1.5 mg/L during the entire period (data not shown). It could be concluded that the module could provide a water permeability of about 8 $Lm^{-2}h^{-1}bar^{-1}$ or more (can be higher on-site, as ground waters usually have less than 15 mgTOC/L, assumed in this study), with high quality (very low organic content and free from pathogens) for long operation times or cycles.

THE MICRO-ENTERPRISE CONCEPT

As per the European Union, a company with "fewer than 10 employees and an annual turnover or balance sheet below €2 million" is termed as a micro-enterprise. This study hypothesises that in developing regions with economic water scarcity, a micro-enterprise can produce sustainable and safe drinking water from locally available water resources using a pilot-scale nanofiltration unit and deliver potable water at reasonable prices. A schematic of different operations in such a micro-enterprise or drinking water company is shown in Figure 7.



1. Ground water extraction from an existing well or bore-hole
2. Pre-filtration using cloth filter (if needed)
3. Nanofiltration using ET-System
4. Re-filling of clean 20L container (disinfected)
5. Delivery of water and return of empty container – door-to-door

Figure 7. A sketch of operations in a micro-enterprise in a rural area [from Ahmad (2015)]

Based on the experimental results, it would be appropriate to consider an average water flux of 60 $Lm^{-2}h^{-1}$ at 8 bar (recommended optimum pressure in literature). Thus, with 20 hours operation per day, the ET-System (with $1m^2$ membrane area) can produce 1200 L of high quality water per day, sufficient to meet the needs for drinking and cooking of 120 five-member-households as per Ghana Statistical Service (2014). Table 3 presents an estimate of the costs (fixed and variable) and the revenue for a micro-enterprise. It has been assumed that the nanofiltration unit shall be chemically cleaned (using solutions of NaOH and HCl) once in every two weeks, thus operating for 336 days a year (6720 operating hours) producing $403.2m^3$ clean water per year. It is assumed that an existing bore-hole or a well can be used as the raw water source. The ET-System has a life of 24,000-30,000 hours and an average of 27,000 hours (4 years) has been used in the calculations.

From Table 3, with just one employee, turnover in first 4 years amounts to about €3000 and to about €6300 for every 4 years thereafter, which can be used for other costs not considered in this evaluation. Requirements for land, electrical, mechanical and civil investments are minimal for the establishment of such a micro-enterprise. Miscellaneous expenses (costs for storage tanks, other maintenance works, pre-filtration, water quality analyses, etc.) and taxes (e.g. ground water extraction, brine disposal) have not been included in the estimate. The electricity costs can be reduced to a third, if obtained from energy providers based on renewable sources (GIZ, 2016). There might be a scope for hiring another employee or reducing the water prices further.

Table 3. Fixed & variable costs and revenue for proposed drinking water company - an estimate

Fixed costs - for first 4 years		Variable costs	
One-time investment	Cost (in €)		For 4 yrs. (in €)
ET-System (trade discount possible)	3000-4500[1]	For electricity (€0.3 per kWh)	6050[3]
20 L water containers (250 nos.)	500[2]	For chemicals (€2.6 per month)	125
Delivery vehicle (tricycle cart)	500[2]	Personnel cost (per employee)	3000[4]
Initial investment for 4 yrs. (total)	4000	Total variable costs	9175
Fixed costs (for every 4 yrs.) after first 4 yrs.		Revenue for 4 yrs. (in €)	
Motor plus pump (aft-shop.de)	500	Water cost (€0.01 per L)	16,125
Membrane (replacement, RTS)	150[1]		
Total fixed cost after first 4 yrs.	650		

1 - personal communication, 2 - www.alibaba.com, 3 - www.ecgonline.info, 4 - Ghana Statistical Service (2014)

CONCLUSION

About 663 million people worldwide lack access to 'improved' drinking water source; is often misinterpreted. On the contrary, more than 1.8 billion people do not have access to safe drinking water. Nanofiltration has been widely studied or implemented in industrialised countries for the production of high quality drinking water. This study investigated the feasibility of establishing micro-enterprises for producing potable water using a pilot-scale nanofiltration system in developing countries. Ground water was considered as the raw water source for drinking water production. It was found that a micro-enterprise using a pilot-scale nanofiltration unit can produce adequate water of high quality, for less than €0.01 per litre, for meeting the potable water needs (for drinking and cooking) of a village (with about 600 inhabitants) in a developing country. Micro-enterprises employing nanofiltration can be a solution for the production of safe drinking water in rural areas with economic water scarcity.

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