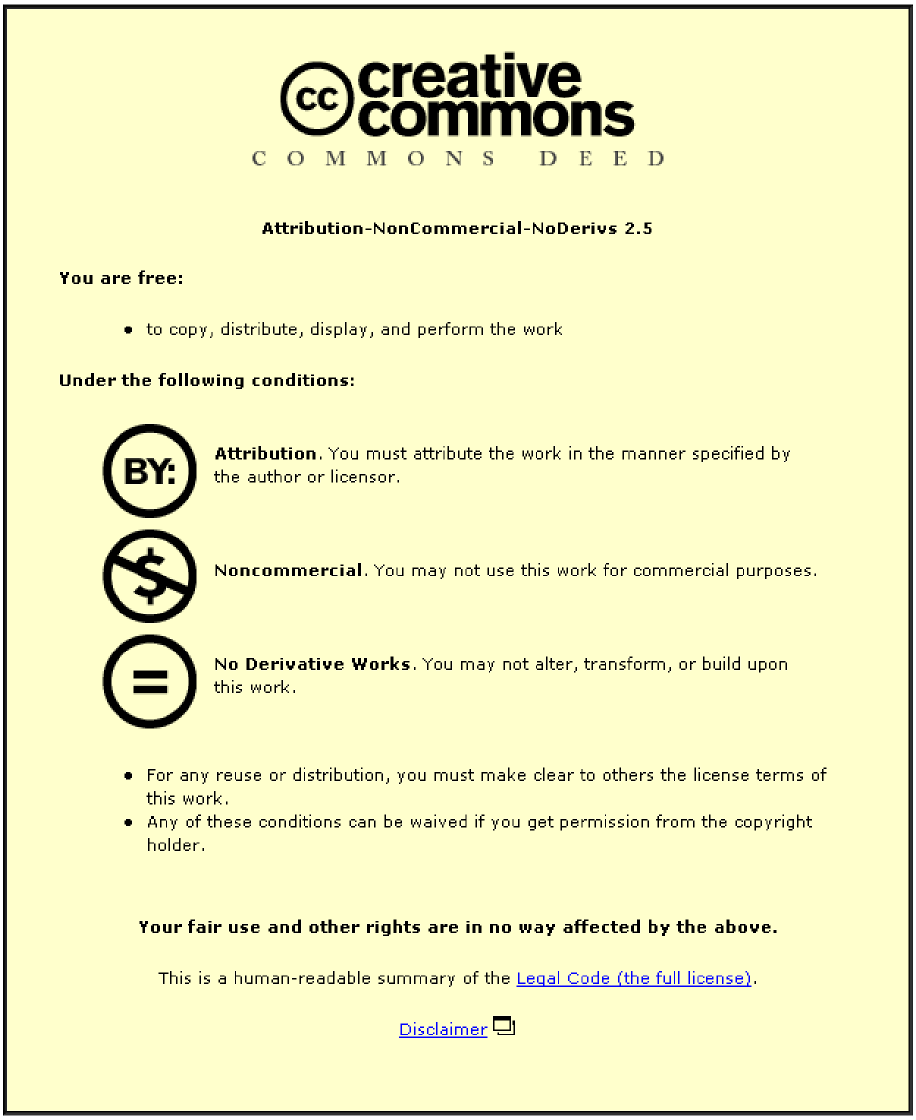

Membrane-based point-of-use water treatment (PoUWT) system in emergency situations: A review

N Shamsuddin, D B Das*, V M Starov

Department of Chemical Engineering, Loughborough University, LE11 3TU, UK

*Corresponding author (Email: D.B.Das@lboro.ac.uk)

Abstract

During emergency situations, effective and quick reactions are vital in order to supply safe and unpolluted drinking water within approved guidelines Point-of-use water treatment (PoUWT) system, for instance, portable membrane-based water treatment devices, could help affected people to survive while waiting for aids to arrive. In the context of portable membrane-based water purification devices, it is also found that the most literature does not mention particle depositions and interactions, and membrane fouling mechanisms that might occur in these devices. The latter is especially important if the device is for private use for certain type of contaminant. It is found that the information available in the literature is mostly based on the performance of devices in terms of the following: bacteria/viruses/particles removal, cost efficiency including maintenance and repair, capacity and flow rate of permeate and producing company. These are discussed briefly as well.

Key words: Membrane filtration - fouling substances - portable membrane-based water treatment device – fouling mechanisms – membrane interactions – emergency situations

1. Introduction

Human body comprises of approximately 80% of water. Hence, in order to survive one must drink at least 3 to 5 litres of water daily to maintain the required water balance in the body [1]. In the events of emergency such as natural disasters (e.g., flood, earthquake, hurricane, etc.) or man-made disasters (e.g., political unrest, wars, etc.), one may not have access to clean and safe drinking water supply due to the destruction and disruption of the necessary infrastructure and facilities [2-4]. Therefore, the need for providing drinking water is often beyond the capability of relief agencies or local governments to respond effectively. One of the potential solutions in this case is to deploy bottled water to the affected population but this approach may not work when transportations are cut off and the affected areas are inaccessible. Researchers have been investing considerable efforts to determine possible ways to filter contaminated water using as little energy and chemicals as possible to minimize harmful effects to the affected population's health while waiting for aid to arrive. The inevitable fear of disease outbreaks in disasters aftermath have motivated scientists to come up with innovative ideas to ensure the survival of population. Decentralized water treatment systems are recognized as one the solutions used for emergency response [5-7]. Peter-Varbanets et al. [6] came up with an emergency response method involving ultra-low pressure with dead-end ultrafiltration (UF) without backflushing and cleaning. Another example is a portable mouth-suction device developed by LifeStraw (Clasen et al. [8] and Frandsen [9]), which is an ultrafiltration (UF) membrane-based purification water technology. These types of device are considered below in more detail.

Water contamination due to an emergency varies significantly from case to case. For example, turbidity of up to 10,000 Nephelometric Turbidity Units (NTU) has been observed in floodwater during the great tsunami of 2004 [10]. Such high level of turbidity makes it hard to treat the contaminated water for drinking purpose in emergency situation. Nevertheless, over the last decade membrane technology has attracted significant interests from researchers for its reasonable quality of production and cost efficiency for use in emergency situation. Membrane processes are not only considered to be cost effective but also they are safe and feasible to operate especially in the times of emergency [11-13]. Furthermore, membrane filtration processes offer relatively simple operation conditions in comparison to conventional methods such as slow sand filtration [14], filtration/disinfection [15] and flocculation/chlorination [16].

In a portable water purification kit, such as point-of-use water treatment (PoUWT) technology, several interdependent and coupled processes take place, such as, various types of interactions between particles, water and membrane materials. It is therefore important for designing of these systems to understand these processes as well as quantify them for a specific case. Requirements of the PoUWT technologies [17] which are used to treat contaminated water for individual or family's drinking and cooking are as follows: (1) could be used to supply drinking water only to accommodate a small number of people and, (2) appropriate for short term response while waiting for aid to arrive and, (3) low cost. Portable devices offer advantages as compared to conventional water treatment systems because such systems are compact, flexible, and easy to use, require fewer chemicals and usually work without electricity. It also seems that none of the published papers (e.g., Ray et al. [18]; Loo et al. [19]; Peter-Varbanets et al. [6]; Ogunyoku et al. [20]) have reviewed the hydrodynamics of the systems, in particular, the hydrodynamic in the membrane-based PoUWT systems. Furthermore, the range of membrane-based PoUWT systems discussed in these papers are restricted to the development context and selection criteria for emergency use.

In this review paper, various aspects of membrane filtration technology, specifically, interactions between the fouling substances in the feed solution with membrane surface and between themselves are critically discussed in the context of portable water purification system. Depositions and interactions of particles suspended in the feed solution are important phenomena encountered in regards to membrane fouling and therefore they are discussed. The suspended particles can deposit and aggregate, which may lead to gradual decline in the permeate flux. The latter is referred to as membrane fouling. Operational parameters such as particle size, pH, ionic strength and transmembrane pressure (TMP) have significant influence in controlling the rate of fouling which are briefly discussed as well. A selection of PoUWT systems is also reviewed briefly.

2. Emergency situations and vulnerable regions

An emergency situation is a "situation arising in the aftermath of a disaster, which may result in "a serious disruption of society, involving widespread human suffering and physical loss or damage, and stretches the community's normal coping mechanisms to a breaking point" [21]. Natural disasters can be viewed as "disruptions of the ecological system" which can "exceed the community's capacity to adjust", thus requiring "external assistance" [22]. Disasters include man-made disasters, (e.g., conflicts and political turmoil resulting in violence), or natural disasters (e.g., drought, hurricane, tsunami, tornado, flood, typhoon and earthquake). Aside from immediate death and destruction, lack of immediate clean drinking water supply to the affected population is inevitable. More than 90% of the disasters occurred naturally where 95% of the disasters occurred in the developing countries [23]. Regions such as Asia and Pacific are regarded as the most affected regions by natural disasters [24].

For example, the great East Japan earthquake in 2011 was the greatest earthquake in Japan's history with severe destruction of large amount of buildings and infrastructure [25-27]. Meanwhile in Indonesia the tsunami of 2004 had led to substantial population displacement with more than 500,000 people's death, and the spread of transferrable infections are among the main source of death in the aftermath of the disaster [28-29]. Emergency Events Database (EM-DAT) compiled important data from various sources on the occurrences and effects of disasters in the world from 1900 to the present. Table 1 shows example of disasters caused by flooding and significant damages and deaths resulted from such events.

Republic of China suffered the very significant impacts on its population with about 37,000,000 people were killed during floods in 1931 in the same country as can be seen in Table 1. Figure 1 shows vulnerability of Asia and Americas to natural disasters and especially flood disasters when compared to other countries. The vulnerability of regions such as United States and Asia to catastrophic disasters exacerbates the impact of disasters in terms of human casualties, environmental disruptions and economic losses.

Continuous and reliable source of clean and safe drinking water in emergency situations is among one of the top priorities after a disaster. It is very important to avoid the transmission of waterborne diseases which is one of the major concerns; hence, a fast and efficient response to build and establish proper water treatment system is required for the affected population to survive. However, such treatment is limited and difficult due to the inability to access the infrastructure during disaster, and also variable water quality [19].

2.1 Drinking water quality and guidelines during emergency situations

The major aim of any emergency response in supplying drinking water is to save human lives. However, it is also important to meet either the national or international drinking water guidelines. According to Brown and Murray [28], flooding can cause significant increase in microbial contamination of surface water. Drinking these dirty and contaminated waters may cause severe health complications and risk lives. The severity of water contaminants such as harmful substances e.g., bacteria, viruses, protozoa and others [30-32] and chemical pollutants [33] makes conventional water treatment systems fail to operate and deliver good quality of drinking water. Therefore, it is essential to consider acceptable water quality guidelines and have an equal balance on short and long term risks for human consumption. In the case for short term response, it is normally better to supply enough water with intermediate quality than supplying little water with high quality for survival purposes [34-36]. However for the long term response, serious amount of attention must be given to ensure that the guidelines are met in order to avoid chronic health effects to the affected population [37].

2.2 Flood water characteristics

Table below shows several flood water characteristics in natural disasters. Wide range of values reported due to differences in geographical landscape and environmental factors.

Table 2 provides some example characteristics of flood waters in disasters-prone countries such as Indonesia, India and Bangladesh. Three main parameters amongst others were measured to understand the severity of the disaster. Garsadi et al. [10] reported qualities of raw water in the aftermath of tsunami in Indonesia. Turbidity of raw water was very high with a range between 300 to 16,000 NTU. Total dissolved solids were measured to have values between 100 to 400 ppm, while pH was reported to have values of 7 to 8.3. During flood in one of the states in India, Andey et al. [38] measured the turbidity to be around 70 to 300 NTU with total dissolved solids at 150 mg/l and pH of at maximum 7.8. Sirajul-Islam et al. [39] investigated the water qualities during flood in Bangladesh. They reported that the total dissolved solids was less than 400 mg/l and pH reached maximum at 7.8.

Natural disasters such as floods and hurricanes caused severe water contaminations hence hazardous for human consumption. Such contamination requires immediate treatment otherwise waterborne diseases could easily spread and cause epidemic.

2.3 Outbreak of waterborne diseases

Ingestion of 1 to 10 viral particles can have significant chances of infection as enteric viruses are highly contagious [40]. In developing countries, diseases such as hepatitis A/E are regarded as common infections reported where sewage management and hygiene system are poorly managed. Following the 2004 Indonesia tsunami, those virals were also detected among the affected population in Banda Aceh [41]. Polluted water, soils and food which contain leptospires, i.e. contaminated urine from infested animals (rodent-borne) can cause the spread of leptospirosis [42-43].

Studies showed that the frequency of infectious diseases can dramatically increase in weeks to months after flooding. This is illustrated in Figure 2, which shows the time period outbreaks of infectious diseases following flood disasters. Three common and main disease outbreaks following floods disasters reported are water-borne, rodent-borne and vector-borne [16]. Floods usually cause population displacement and subsequently changing the population density. The main concerns include management of wastes and supply clean and safe drinking water to the affected population. Important that due to damages to infrastructures and facilities, health care centres and services might not be accessible for immediate treatment. Therefore to ensure survival, it is wise to own a PoUWT system to effectively treat contaminated water while waiting for aid to arrive.

3. Applications of membrane filtration in emergency situations

The volume of research and development of membranes have expanded considerably over the last 20 years with new ideas and more development directions have emerged. Membrane surface modification emerged as a new way to enhance the membrane performance in terms of improved permeate flux and lower fouling rate, which is a result of weaker interaction of fouling materials with modified membrane surfaces [44-45]. Such modifications techniques include plasma treatment, physical coating of hydrophilic layer on membrane surface, use of nanoparticles for surface modification, and chemical reactions on membrane surfaces [33]. Another new application is the development of hybrid materials which combines photo-catalysis with membrane technology [46].

Applications of membrane filtration have expanded rapidly for both particulate/microbial removal and for a removal of a host of particulate and dissolved contaminants (see Table 3). Each membrane has specific characteristics. This resulted in an increase in competition between companies producing membranes and, in turn; membrane technology is now becoming an economically feasible process. Membrane filtration offers a rather simple operation and a low cost in comparison to conventional methods. There is no doubt that this technique has a large potential application as more researchers try to design portable water purification systems, which are practical and appropriate in times of natural disasters.

To obtain adequate amount and of a reasonable quality drinking water may be difficult in various regions especially for the affected populations in developing countries and after disasters. The situations will aggravate as cases of natural disasters continue to increase with increasing frequency and intensity for years to come. Therefore, it is essential that the aim for any aids from the government agencies or authorities following disasters is to prevent infectious viruses or epidemics from spreading quickly to the affected population by supplying good quality drinking water for consumption. A review of portable and non-portable membrane-based drinking water treatment methods used in emergency cases is therefore presented in the following section. The important parameters affecting the performance of portable water purification systems are discussed.

3.1 Emergency water treatment during natural disasters

There are two conventional ways of providing potable water to the affected population during emergencies and population migration. The first is to package treated water and transport it to the site. However, due to environmental constraints this transportation could not provide immediate supply of clean water. While immediate response is needed, conventional treatment plants could not carry out normally as planned and consequently fail to supply in the long run. Another way to have drinking water is by boiling process. This method was reported to successfully eliminate microorganisms in the water but recontamination was the main concern.

The use of point-of-use water treatment (PoUWT) technologies has been a promising alternative method to provide access to clean and safe drinking water in emergencies. Such technologies are flocculants, ceramic filters, disinfectants, sand filters and solar disinfection (SODIS) [11]. These technologies have been proven for their effective through many controlled studies (Brown et al. [47]; Elliott et al. [14]; Doocy and Burnham [16]; Stauber et al. [48]; Clasen et al. [49]; Conroy et al. [50]; Powers et al. [51]; Wegelin et al. [52]; Hoque and Khanam [53]).

However, many PoUWT technologies are more suitable for household based needs either for counter fitting or on a table top especially in developed countries where these technologies are readily available and affordable [54]. It was reported that most of PoUWTs are generally made in China, Korea, Taiwan and United States [55]. In developing countries, it might not be the case as the people may not be able to afford to buy these technologies because they are quite expensive. Hence, the use of PoUWT technologies in developed countries could potentially lessen the problems with contaminated water when disasters happen but not in developing countries. Whereas point-of-entry water treatment (PoEWT) technologies are more common in both developed and developing countries as part of government's emergency plans to supply clean and safe drinking water to the affected population.

Many available membrane-based water purification systems are PoEWT technologies designed for treating contaminated water for larger communities rather than for individual usage. Moreover, limited information is found in literature on PoUWT technologies like portable membrane-based water purification devices being used in the aftermath of disasters. For example, in floods where people got stranded on trees and roof tops. Most portable membrane-based water purification devices are available for travellers and hikers usage [56]. Moreover, it is crucial to note that in the aftermath of natural disasters, immediate response is absolutely essential to ensure the survival of the affected people. Though companies and organizations have made significant efforts to design suitable water treatment systems, there are still many constraints faced as previously mentioned.

Table 4 shows available portable membrane-based water purification devices on the market. Common membranes used are microfiltration (MF); followed with ultrafiltration (UF), reverse osmosis (RO) and forward osmosis (FO). As stated in Table 3, most microfiltration (MF) and ultrafiltration (UF) membranes can successfully eliminate microorganisms of size range between 0.1-5 µm such as bacteria, viruses and protozoa and require minimum pressure to operate the system [57-58].

Meanwhile reverse osmosis (RO) membranes are usually are excellent in getting rid of high molecular compounds and dissolved inorganic pollutants ([59], [60]). However, the operating pressure is a lot higher than in ultrafiltration (UF) and microfiltration (MF). Forward osmosis (FO) membranes are interesting because the performance of the membranes is quite comparable to ultrafiltration (UF) membranes without applying any pressure to force the fluid flow across the membrane. With forward osmosis (FO) membrane used in hydration bags where a disposable nutrient solution filled in a semi-permeable barrier carrier bag [6]. Due to osmotic pressure difference, surface water diffuses through the membrane leaving behind contaminated materials and consequently attenuates the initial solution. This later can be drink as it contains minerals and nutrients.

Table 5 presents a summary of water purification technologies used during natural disasters. Most of the technologies are not portable but rather mobile for easier deployment to the affected areas in the aftermath of disasters. Several technologies use conventional treatment which involves media filtration, flocculation and coagulation depending on the severity of the affected area and availability of facilities. The use of membrane-based technologies has gained its popularity over the recent years.

3.2 Parameters affecting performances of portable membrane-based water purification device

The nature of fouling substances in the feed solution and membrane properties determine performance of a membrane-based water purification device as discussed earlier. Therefore, it is very important to choose appropriate materials when manufacturing membranes to minimize such effects. These issues currently continue to be part of significant research and development efforts.

3.3 Membrane properties

3.3.1 Hydrophilic and hydrophobic surfaces

Membranes can be made of either hydrophobic or hydrophilic materials and these have influence on the membrane permeability during filtration processes. It is generally believed that hydrophilic membranes give greater performance than hydrophobic ones against organic and biological fouling caused by materials found in the feed solutions such as bacteria, proteins and natural organic matter (NOM) [61]. Hydrophilic surfaces have higher surface free energy as compared to hydrophobic surfaces. Fouling materials such as oils work better with hydrophobic surface as hydrophobic surfaces have low surface free energy hence reducing the effect of adhesion to the membrane surface. For hydrophilic surfaces with higher free energy than the oil-water interfacial tension will cause the oil spreading on the surface of the membrane creating relatively a very small contact angle and hence stronger adhesion to the membrane surface [62]. However, hydrophobic membranes still exhibited poor affinity to water and hence water permeability was very low when compared to hydrophilic membranes [63]. Researchers are trying to design membrane materials in order to obtain high water permeability with low adhesion capability, and also low interaction strength between the concerned fouling materials for membrane surface water treatment and the membrane surface. A study by Zhu et al. [64] proved that a membrane displaying both oleophobic and hydrophilic surface properties has both greatly enhanced water flux and decreased the rate of organic fouling.

3.3.2 Surface morphology

Membrane surface morphology is important for understanding of membrane fouling. Surface morphology can be analysed using scanning atomic force microscopy (AFM) and electron microscope (SEM). Wu and Wu [65] have characterized the essential parameters that define membrane morphology. Such parameters include nominal porosity, pore geometry and effective distribution of pore sizes, etc. Characteristics of commercially available membranes were investigated by Kim et al. [66] using methods such as biliquid permporometry, thermoporometry, molecular weight cutoff (MWCO) and SEM. From their findings, the use of biliquid permporometry and thermoporometry gave larger pore diameters when compared to MWCO and SEM methods. According to Elimelech et al. [67] and Kim et al. [66], the performace of a microfiltration membrane is essentially governed by the surface roughness of the membrane. According to Elimelech et al. [67] the fouling rate of colloids could be analysed from surface roughness of a membrane. Uneven and rough surface would result in more severe membrane fouling. Wong et al. [68] also reported the same phenomena of surface roughness on adhesion (fouling) nature of membranes. These studies show that there is a strong relationship between membrane fouling and surface roughness and these relationships should be inferred for the membranes used in portable water purification kits used for emergency situation.

3.3.3 Surface charge

Membranes having the same electrical charge as the fouling particles/proteins/bacteria are favourable as to promote electrostatic repulsion forces between fouling materials and surface of the membrane, thus reducing the effect of depositions and fouling [45]. Incorporating membrane surface with ionisable functional groups is one of the solutions to reduce the effect of fouling. Membrane surfaces with negative charge at neutral pH enhance protein rejection because most proteins are negatively charged at neutral conditions [69]. Colloidal materials such as NOMs are negatively charged, hence, using negatively charged membrane would reduce the depostions of NOMs on the membrane surface. Therefore, it is essential to consider these factors on choosing membranes for minimization of the effect of membrane fouling.

3.3.4 Membrane pore size and porosity

Cui et al. [44] examined the influence of membrane pore sizes on permeation rate as pre-treatment for reverse osmosis (RO) desalination. Their work used ceramic membranes with different pore sizes of 50, 200, and 800 nm and found that the effect of pore sizes on the permeation rate was insignificant. Tarleton and Wakeman [70] reported that there was insignificant influence on permeation flux of cross-flow MF when the majority of the particles in the feed solution were significantly larger than the membrane pore size. In addition, they found that if the particles in the feed solution were close or smaller than the pore size, the permeate quality and rate were often worse. Altmann and Ripperger [71] claimed that large particles were more difficult to cause fouling than smaller particles in MF. This phenomenon can be further explained with the Kozeny equation that articulates the specific resistance (R_C) of an incompressible cake. According to the equation, the cake-specific resistance increases if both porosity of the cake/gel (ε) and diameter of the deposited particles $\left(d_p\right)$ decrease:

$$R_C = \frac{180(1-\varepsilon_C)^2}{{d_p}^2{\varepsilon_C}^2} \qquad (1)$$

Where d_p is the average diameter of the particles deposited and ε is the porosity of gel/cake [72].

Membrane porosities can be determined experimentally using various direct methods namely: water pycnometry, apparent densities, gas penetration technique and mercury (Hg) porosimetry [73]. Whereas there are also other computerized analysis or indirect methods: air-liquid displacement techniques and SEM [73]. Generally, it observed that high porosity is associated with large pore size and less oriented structure. Therefore, choosing membranes with high porosity will result in increase in water permeability across the membrane.

3.4 Operational conditions of water purification device

There are a number of various operational conditions, which have significant effect on the permeation rate: particle size, ionic strength, pH, cross-flow velocity, concentration and transmembrane pressure. The variation of pH may affect the permeability of the membrane [74-78]. Depending on the solution chemistry, a morphological change membrane surface or contaminants can be enhanced. Feed contaminants having isoelectric points that are close to the pH of the membrane surface will result in an attraction force. This is because the electrostatic repulsion force is at minimum. Membrane material can also be affected by pH. Acidic solutions were claimed to have decreased the thickness of NF membranes [79].

Chang et al. [80] studied the pH effect on the rheology of clay particles. They found that the variation of pH could affect the behaviour of clay particles by influencing its surface charge and hence promotes attraction forces between these particles. Debye length is used to measure the electrical double layer thickness surrounding a charged particle [81]:

$$K^{-1} = \left(\frac{\varepsilon k_B T}{8\pi Z^2 e^2 N_A C_S}\right)^{1/2} \tag{2}$$

where ε is solution dielectric constant, k_B is Boltzmann's constant, e is the electron charge, Z is the ion valence, T is absolute temperature, C_S is electrolyte concentration and N_A is Avogadro's number.

This relationship showed that double layer thickness decreases if the electrolyte concentration increases. The vast majority of natural solid particles are negatively charged at high pH and positively charged at low pH. Hence, low ionic strength and high pH will result in a thick electrical double layer, whereas low pH and high ionic strength cause thin electrical double layer and lower repulsion.

The influence of particle sizes on filtration rate and fouling was investigated by Wakeman [82]. Wakeman [82] concluded that the smallest particles are the ones causing the most influence at the initial stage of filtration process as these particles could enter the pores, which results in pore blocking, and accumulate on the membrane surface forming cake layers. Wakeman [82] also found that larger particles tend to prevent severe pore blocking. Some examples of influence of different particle sizes of fouling materials in membrane filtration processes are shown in Figure 3.

Zhong et al. [83] investigated the influence of cross-flow velocity on UF flux for recovering titanium silicate catalyst from slurry. It was known that increasing the cross-flow velocity is considered to be an effective method to prevent particles deposition on the surface of the membrane, and, hence, to prevent fouling. However, it is impossible to re-suspend the deposited particles from the membrane surface due to strong attraction force which is higher than the lift forces at such high cross-flow velocities. The same phenomenon was also described by Ripperger and Altmann [84]. Cheryan [85] claimed that particles which are bigger than the membrane pores could be induced under shear force generated by cross-flow velocity, this caused the membranes to become mobilized on the membrane surface thus limiting the effect of fouling. This might not be the case for particles which are smaller to that of membrane pores. These smaller ones could penetrate the pores against the shear force thus promoting membrane fouling. Therefore, effective cross-flow velocities needs to be optimized in order to minimize the effect of such fouling.

The concentration of the fouling substances in feed solution has a significant influence to the resulting permeate flux. Guiziou et al. [86] showed that increasing the latex suspension up to 3 grams per litre gave linear decrease in the permeate flux in MF membranes. Shamel and Chung [87] reported that increasing feed concentration decreased permeate flux thus needing much higher driving force i.e. pressure to drive the permeate across the MF membrane. High feed concentration could result in accummulation of particles on the surface of the membrane and eventually over a period of time, fouling can be observed. Moreover, a greater concentration of solutes can lead to a greater concentration polarization which may lead to a higher degree of membrane blocking during filtration process, which results in a greater retention of solutes [88-90].

Membrane filtration system (UF or MF) can either be operated in dead-end or cross-flow configuration. The schematic diagrams of the two modes are shown in Figure 4. In dead-end operation, feed is forced through the membrane and permeate comes through the membrane, leaving the rejected solids on the membrane surface accummulated continuously**.** Thus, continually reducing the permeation rate and eventuallly leading to membrane fouling. Moreover, in cross-flow operation, most of the feed flows along the surafe of the membrane rather than passing through the membrane structure.

Operating parameters such as transmembrane pressure plays important role in membrane separation processes especially in pressure-driven processes. Not only it drives the liquid through the membrane, there is also considerable experimental evidence that MF, UF and reverse osmosis (RO) membranes can compact under pressure which results in significant changes in permeability [91]. Stade et al. [92] studied the impact of compaction on UF membranes. From their investigations, regenerated cellulose (RC) membrane compacted significantly more than polyethersulphone (PES) membranes. The reasons are due to different membrane material and significant differences in the membrane structures. Compaction of the skin layer resulted in the decrease in permeabilty and increase in retention [92]. Membrane compaction can lead to irreversible flux decline even at relatively low filtration pressure as reported by Kallioinen et al. [93], Tessaro and Jonsson [94], and Persson et al. [95]. Belfort et al. [96] measured the thickness of cellulose acetate membrane using scanning electron microscope (SEM) and found the compaction effect occurred in less than 15 minutes and at pressure lower than 1MPa. According to Peterson et al. [97] claimed that the compaction effect arised from the deformation of support layer of a cellulose acetate membrane.

Besides decline in flux, compaction can also cause an effect to solute rejection. Compaction could result in the decrease in pore size or a deformation of the pore geometry thus its tendency depends on the precise physical and also chemical structure of the membrane. By reducing the pore size of the membranes, more particles could be retained on the membrane surface thus increasing the percentage of solute rejection although there is contrasting information reported [93,98]. Currently, the study of membrane compaction of UF in water treatment has not been extensively published hence limited, although this information is valuable for optimizating the process.

3.5 Particle deposition and interactions, and membrane fouling in UF and MF membranes

It is important to note that most information in the literature does not specifically mention: (1) particle depositions and interactions and (2) membrane fouling mechanism that occur in the context of portable membrane-based water purification device. Rather, the information shown is based on the performance of the device in terms of the following: (1) bacteria/virus removal, (2) cost, (3) maintenance and repair, (4) capacity and flow rate of permeate and (5) manufacturer’s data (see table 4), especially if it is valid for commercial use. Therefore it is a challenging search to review based on limited information available. However, the principle theories should give a better understanding on how such phenomena occur in a typical membrane filtration processes such as UF and MF. Moreover, a numerous information is available in the literature based on water treatment for larger systems, i.e. wastewater treatment, desalination etc.

3.5.1 Depositions and interactions

Belfort et al. [99] reviewed that adsorption of protein onto membrane surface which caused flux decline was only a minor part, but it was protein deposition during dynamic and convective flow that caused the major contribution towards membrane fouling. There are many studies reported on membrane fouling analysis in UF membranes and in MF membranes [100-102]. Membrane blocking models are theoretical hypothesis which can be used to describe the deposition of accumulated particles on the surface of the membrane [103-107].

Howe and Clark [108] claimed that particles of less than 0.45 µm is insignificant in causing membrane fouling as it can be detached in backflushing cycle. However, it was those very small colloids of size range between 2 to 20 nm are significant membrane fouling materials. These colloids can be adsorbed onto the internal wall of UF and MF membranes thus increasing membrane hydraulic resistance and consequently caused pore blockage. Membrane fouling caused by mixtures of different fouling materials which include organic, inorganic colloids and natural organic matter (NOM) is more complicated. A few studies investigated the result of combined mixtures of inorganic, organic and NOMs showed that a higher decline in flux rate observed when compared with filtration of individual fouling substance [109]. Three mechanisms played important role in combined fouling: (1) hydraulic resistance of the mixed cake layer structure increased, (2) hindered diffusion of fouling substances, and (3) organic adsorption caused change to colloid surface properties [110].

Meanwhile, the attachment of colloidal particles onto the membrane surface can be described using the classical Derjaguin-Landau-Vervey-Overbeek (DLVO) theory. The theory states that the sum of the repulsive and attraction forces will determine the net colloid-surface interaction. The equation used to describe the theory is [45]:

$$V_T = V_A + V_R \tag{3}$$

Where V_T is the resultant force; V_A is the attraction force (van der Waals forces) between particles of identical nature and V_R is the repulsion force (electrostatic repulsion/electrical double layer force) between similarly charged colloidal particles.

Van der Waals attractive interactions between two identical spherical particles are given by the following expression [45]:

$$V_A = -\frac{Aa}{12h} \tag{4}$$

Where A is the Hamaker constant (attraction parameter); a is the radius of a sphere and h is the inter-particle distance. The Van der Waals attractive interaction between two sheets (plate-like particles) of identical physical nature is given by the following expression [45]:

$$V_A = -\frac{A}{12\pi h^2} \tag{5}$$

The surface charging in water can be caused by two mechanisms [111]; (1) ions adsorption from solution onto uncharged surface, and (2) by the ionization of surface groups. Both mechanisms result in the formation of the surface charge. When particles with identical charges approach each other, their electrical double layers start to overlap, thus creating a repulsion force. This repulsion force can be calculated as follows Gregory [112]:

$$V_R = \frac{128\pi a_1 a_2 n_\infty k_B T}{(a_1+a_2)K^2}\gamma_1\gamma_2 exp(-Kh) \tag{6}$$

Where a is the radius of particle of different sizes; K is the Debye-Hückel-reciprocal length; h is the surface-surface separation between the colloidal particles; γ is the reduced surface potential; and $n_\infty$is the bulk density of ions.

To summarize, it is essential to have good understanding of the characteristics of fouling substances in the feed solution such as its surface and hydrodynamic interactions with other fouling substances and also with the membrane materials, particle sizes, molecular structure of fouling substances and the presence of chemical and physical bonds. These characteristics contribute the extent of membrane fouling.

3.5.2 Membrane fouling mechanisms for particulate/colloidal fouling in UF and MF membranes

Fouling of the membranes is no doubt an important limitation in membrane-based water treatment. According to Rudolf and Balmat [113], the classification of particulate matter in wastewaters and natural waters can be divided into four main categories: (1) settle-able solids with particle size range of more than 100 µm, (2) supra-colloidal solids size range between 1 µm to 100 µm, (3) colloidal solids with particle size range between 0.001 µm to 1 µm, and (4) dissolved solids of less than 10 Å.

Hermans and Bredeé [114] first proposed blocking filtration laws. It was further developed by Gonsalves [115]. Grace [116] first discovered, in series of experimental studies with a number of membranes, the presence of standard blocking in each micro filter used. It was Hermia’s [117] work that combined all four blocking mechanisms for dead-end filtration based on the Darcy’s law and since then the models have been used extensively and modified thus becoming the basis of modelling filtration processes. The mechanism for membrane blocking models is illustrated in Figure 5.

The type of membrane fouling greatly influenced by the particle sizes, which can be either similar or smaller or larger than the pore size of the membrane. In the complete pore blocking or pore sealing, where particles reach a membrane and are of the same size as the pore size hence the pore is blocked without superposition of other particles. This causes a reduction in active membrane area. Hence less permeate flow through the membrane, and the surface area blocked by the particles is said to be proportional to the permeate volume.

During partial pore blocking, particles of similar size with membrane pores deposit on the surface of the membrane and consequently block the pores. Generally, it is presumed that these particles are adsorbed chemically to the membrane surface, and also include the fact that there are arriving particles to the membrane surface which already blocked by the adsorbed particles. Meanwhile in pore constriction, due to the size of the particles which are smaller than the membrane pore sizes, these particles could penetrate the pore and hence this can cause irreversible fouling. Because of this reason, the membrane pore volumes proportionally decreases with the volume of permeate. And lastly, cake formation is a condition where particles continue to deposit on initial layer of particles and as soon as the cake formed. The particles maybe smaller or larger than the membrane pore size [118-120]. The cake creates additional resistance to the permeate flow.

A mathematical expression can be used to describe flux decline at constant pressure for dead-end filtration:

$$\frac{d^2t}{dV^2} = k\left(\frac{dt}{dV}\right)^n \tag{7}$$

Where n is the blocking index and k is the resistance coefficent which depends on the blocking models; t is the filtration time and V is total permeate volume collected. For complete pore blocking $n = 2$; for partial pore blocking $n = 1$; for pore constriction $n = 3/2$; and for cake formation $n = 0$. Integration of the above expression leads to Hermia models in Table 6, where J_0 is the initial flux.

Peter-Varbanets et al. [121] studied the mechanisms of membrane fouling in their ultra-low pressure UF system. A summary of the mechanisms is shown in Table 7. In Table 7, from their findings, the fouling layer was controlled by changes in the structure and undissolved materials which deposit on the membrane surface. Both deposition and irremovable fouling contribute to an increase in resistance over time. Another cause of increase is due to the physico-chemical interactions which resulted in the formation of channels in the fouling layer. They concluded that concentration of biopolymers and low molecular weight (LMW) compounds, concentration of humic acids (HA) and dissolved oxygen (DO) conditions in the feed water are important parameters in controlling the fouling mechanisms.

Combined models have been used in order to further undestand the mechanism of fouling, as these mechanims happen simultaneously in a filtration. Ho and Zydney [122] proposed a combined pore blockage and cake filtration model for protein in MF process. From their findings, there was a smooth change from pore blockage and cake formation observed. Their models have been used extensively and modified accordingly by researchers since then [123-125].

A coupled three mechanisms model was developed by Duclos-Orsello et al. [126] which accounted for three conventional fouling mechanisms namely; pore blockage, pore constriction and cake filtration. Iritani et al. [127] and Lee [128] are among other researchers that used more than one blocking mechanism to describe the fouling.

3.5.3 Concentration polarization

Concentration polarization is said to be the final phase of fouling. It is a phenomenon where particles concentration in the area of the membrane surface is greater than in the bulk solution, resulting in the back diffusion. Concentration polarization increases the potential of fouling and deteriorate quality of permeate. The decrease in permeation rate happens as osmotic pressure and hydraulic pressure increase.

Cake enhanced concentration polarization (CECP) or cake enhanced osmotic pressure (CEOP) is a condition where back diffusion of the retained particles from the membrane surface which is fouled, to the bulk solution is slowed down and hence cake layer is formed [129-131]. In this condition, the particles need to diffuse longer through tortuous channels within the cake layer. Hence increasing further the osmotic pressure at the membrane surface will lead to the loss of transmembrane pressure (TMP) effectiveness; which means TMP is no longer having an effect on flux.

Filtration number, N_F, represents the ratio of energy required to move the particles from the surface of the membrane to the bulk, to the thermal energy of the particles. It was first proposed for cross-flow filtration by Song and Elimelech [132]:

$$N_F = \frac{4\pi {a_p}^3 \Delta P}{3kT} \tag{8}$$

Where a_p is the particle size, ΔP is the transmembrane pressure (TMP), k is the Boltzmann constant, and T is absolute temperature.

If thermal energy of the particles is lower than the energy required for back transport, then the particles will stay close to the surface of membrane and consequently a cake layer will form, and vice versa. This situation can be illustrated in Figure 6.

3.5.4 Gel-layer (cake) formation

Formation of gel layer according to Hwang and Hsueh [133] can be categorized into three main phases: (1) pore blockage at the beginning of filtration process. The overall filtration resistance increased due to deposition and reorganization of colloidal particles on surface of the membrane, (2) formation of cake results in further increase in filtration resistance and porosity of cake layer to decrease, this is due to the compression and deformation activities of the deposited colloids, and finally (3) compressed gel layer started to form next to membrane surface. The thickness comprised between 10-20% of the whole cake layer, however this layer shows 90% of the overall filtration resistance. Cake layer is also called ‘stagnant layer’ or ‘immobile layer’ due to deposition of particles, whereas concentration polarization is also named ‘flowing layer’ because the particles are not stagnant and constantly diffusing within the layer.

3.5.5 Limiting and critical fluxes

The presence of the limiting flux is obvious with the formation of gel/cake layer on surface of the membrane [134-135]. Increasing the applied pressure will increase the pressure difference on the concentration polarization layer and consequently permeate flux but no cake formation forms. This flux is called critical flux where there is no cake layer formed on the surface of the membrane [136-137]. However, the presence of fouling substances in the feed solution will cause the particles to block the pores of the membranes and at certain period of time, the formation of cake layer can be observed. Cake formation continues to build up to equilibrium thickness. When this condition reached, increasing the pressure will no longer have an effect on the flux. The maximum permeate flux obtained at this condition is called limiting flux.

For design purposes, the concept of these fluxes represent an important characteristic of membrane operation especially in UF/MF systems [138]. Fouling of a membrane can be shown through the presence of limiting flux and the onset of critical flux [139]. Hence manipulating the operating pressure of the system could maximize the overall performance of the membrane. A comprehensive review on this subject matter can be found through Bacchin et al. [134] work. In their work, the authors reviewed the differences between the two fluxes and clarified misundestandings related to the concept and theories.

4. Conclusions

With increasing frequency and intensity of disasters, one of the main priorities after a disaster is the supply of clean and safe drinking water. However, it is a very challenging task as facilities and infrastructure may not be available due to many factors. Moreover, outbreak of waterborne diseases is one of major concerns because such diseases are infectious and cause deaths. It is essential to own decentralized portable water purification system for short term response for the survival of the affected population. Membrane-based system is considered to be one of the most effective methods to treat contaminated water with high productivity due to several reasons mentioned earlier. The availability of such portable membrane-based PoUWT device in developing countries is not as good as in the developed countries. This is simply because such device can be quite expensive as seen in the tables mentioned earlier. Clearly, more work needs to be done in this aspect and most importantly the availability of related information should be disclosed in the literature for future references. Aspects of membrane fouling and its interactions are discussed, and their importance in the design of water treatment devices is explained.

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Table 1 Most important flood disasters for the periods 1900 to 2013 sorted by numbers of deaths at the country level [24].

Country	Date	No Killed
China P Rep, General flood	July 1931	37,000,000
China P Rep, --	July 1959	20,000,000
China P Rep, General flood	July 1939	5,000,000
China P Rep, --	1935	142,000
China P Rep, General flood	1911	100,000
China P Rep, --	July 1949	57,000
Guatemala, --	October 1949	40,000
China P Rep, --	August 1954	30,000
Venezuela, Flash flood	15/12/1999	30,000
Bangladesh, --	July 1974	28,700

Table 2 Data on a quality of raw water reported in events of natural disasters which include tsunami and floods [10,38,39].

Parameter	Indonesia	India	Bangladesh
Turbidity	300-16,000 NTU	70-300 NTU	N.R.
Total dissolved solids (TDS)	100-400 ppm	148-150 mg/L	37-357 mg/L
pH	7-8.3	7.7-7.8	6.2-7.8

Table 3 Application range of various membranes processes [140].

Range	**Ionic range**	**Molecular range**	**Macro molecular**	**Micro particle**	**Macro particle range**
Particle sizes of pollutants (μm) **MWCO (kDa)**	0.001 0.1	0.01 5	0.1 500	1 10	100
Pollutants	Aqueous salts Small sand		Colloids	Bacteria	
	Metal ion	Latex Emulsion			
	Sugar	Viruses and protein		Cryptosporidium oocysts	
	Atomic radius			Giardia cysts	Pollens
Process for purification	Reverse osmosis				
	Nano-filtration				
		Ultrafiltration			
			Microfiltration		
Usual operating pressure	>0.5 MPa	0.05-0.3MPa		0.01-0.2 MPa	

Table 4 Characteristics of portable membrane-based water purification devices used (as obtained from manufacturers' data and reported in the references).

Name	Operating mode	Filter type	Cost	Production rate	Capacity (litres)	Manufacturer	References
Mini Ceramic® (Travellers/Hikers)	Hand pump	Pre-filter, 0.2 µm (MF membrane) ceramic Ag-impregnated	US$110	0.5 litres/min	7000	Katadyn Product AG Wallisellen, Switzerland	[56]; [141]
WalkAbout® (Travellers/Hikers)	Hand pump	Pre-filter, 0.2 µm (MF membrane) labyrinth depth	US$45	0.7 litres/min	380	SweetWater® Longmont, USA	
First Need Deluxe® (Travellers/Hikers)	Hand pump and gravity	Pre-filter, 0.4 µm (MF membrane) structured matrix, electro- kinetic action	US$129	1.7 litres/min	400	General Ecology, Inc. Exton, USA	
Pres2Pure® (Travellers/Hikers)	Flexible bottle	2 µm (MF membrane) porous plastic impregnated with powdered activated charcoal and other absorbent media	N.R	N.R	750	CrystalPure® USA	
FO filter pouch (Haiti earthquake)	N.R	FO membrane	N.R	1.6 litres/ day	10 days (filter life)	N.R	[142]; [143]
Lifestraw®	Mouth suction or gravity feed	Pre-filter, 27 µm and halogen chamber, 20 nm (UF membrane) hollow fibre with cylindrical cartridge		8.6-12 litres/ hour	18,000	LifeStraw, Vestergaard	[8]; [9]

Modified backpack-based multi-level filter	Hand pump; No battery required	3 stages of filter: 5 µm spun polypropylene, 0.5 µm carbon filter block and UV light disinfection system	US$113	7.56 litres/min	N.R	University of Hawaii	[18]
Portable RO system	Bicycle pump	6 stages of filter: sediment filter, carbon filter, RO membrane filter, carbon filter and UV unit	US$204	N.R	136-179		
Ceramic filters (pots)	Gravity-driven system	MF membrane impregnated with silver as additional disinfection step and prevents formation of biofilm on the filter.	US$10-25	N.R	5000	N.R	[6]
Filter Pen	Mouth suction	MF membranes with materials blend of different polymers	US$50	3.5 litres/day	4 weeks or 100 litres	Filter Pen Co of New Zealand and Flitrix Co of the Netherlands	[144]

Note: N.R=not reported, MF=microfiltration, UF=ultrafiltration, FO=forward osmosis; RO= reverse osmosis; UV=ultraviolet.

Table 5 Characteristics of water purification technologies used in natural disasters and emergencies events.

Name	Filter type	Production rate	Capacity	Cost	Performance	Maintenance	Energy requirement	References
MSWT-01 (flood)	Screen filter, sedimentation tank, and sand filter. Possibility to add UF and disinfectant	1 m^3/hour	18-20 m^3/day	N.R	Turbidity<2 NTU; Colour reduction<7 TCU	N.R	N.R	[145]
Japan Portable Water Treatment (natural disaster)	MF and UF membrane	150 litres/hour	N.R	N.R	N.R	N.R	N.R	
MHMWTP (floods and tsunami in Indonesia)	Hydraulic driven coagulation/flocculation, plate sedimentation, rapid filtration (optional granular activated carbon filtration and chlorine disinfection)	400 m^3/day	10,000-15,000 litres/hour	N.R	Turbidity<0.2 NTU; Residual chlorine <1ppm; TDS<350ppm	N.R	Small generator (5 kW); 1000-2000 W for power supply	[10]
WTS (floods)	RO membrane	N.R	N.R	N.R	N.R	N.R	N.R	
Soda bottle-based RO system (natural disaster)	Series of RO membranes	N.R	2 litres	US$99	N.R	RO filter washed at periodic interval	Bicycle pump	[18]
Slow sand	Bio-sand: 0.90m	27	750	N.R	Removes >99	N.R	No	

filter (natural disaster)	cylindrical container packed with 0.15m of gravel, and 0.70m of silica sand.	litres/day	litres/day		% harmful bacteria.		electro/mecha-nical power required	
AQUAPOT (Africa communities)	UF hollow fibre PES membrane 150 kDa	Feed flow: 2500 litres/hour	N.R	N.R	Turbidity<1 NTU; Total coliforms<2 NMP/100ml; Thermotolerants coliforms <2 NMP/100ml	N.R	N.R	[146]
Skyhydrant (poor developing countries)	0.04 µm MF PVDF membrane	400-1000 litres/hour	5-8 years	US$3500 per unit	Turbidity<0.1 NTU; LRV for particles 2-5 µm >4	40 ml of 10% hypochlorite; 300 g of citric acid powder	Gravity feed or suction	[13]
Low pressure UF (Africa communities)	PS UF capillary membrane 50 kDa	30-40 litres/m^2h	>5 years	N.R	85% NOM; >90% colour removal; 5 LRV bacteria; 3-4 LRV virus	Backwashing for 1 minute for 10 minutes cycle time; CIP when TMP is 80-100 kPa using detergent at high pH	100-150 kPa by feed pump or use water head; recycle pump powered by electricity	[147]
Neeri-Zar (flood)	Sand and gravel filter with disinfectant	6-10 litres/day	N.R	N.R	93-99% bacterial reduction; Turbidity<2.8	Filter cloth is cleaned periodically	No power required	[38]

					NTU			
Emergency water treatment unit (any disaster)	MF membrane module	N.R	200-500 people during first 5-10 days after disaster	N.R	N.R	N.R	Gravity	[148]
Homespring®	UF hollow-fibre developed by Zenon	14-17 litres/min or 840-1020 litres/hour	20,160-24,480 litres/day	US$2700-3000	N.R	Annual maintenance with carbon filter to be replaced once a year	N.R	[6]; [149]
Ultra-low pressure UF dead end	UF membrane	4-10 litres/hour /squared metres	N.R	N.R	N.R	N.R	Gravity	[150]

Note: MSWT-01= Mobile Surface Water Treatment-1m^3 per hour capacity; MHMWTP= Micro hydraulic mobile water treatment plant; WTS=Water Treatment Systems; RO= Reverse osmosis; PES= Polyether sulphone; PVDF= Polyvinyldiflouride; PS= Polysulphone; LRV= Log reduction value; NOM= Natural organic matter; CIP= Clean in place; TMP= Transmembrane pressure

Table 6 Hermia blocking laws and examples of modified Hermia's blocking laws done by other researchers found in literature.

Fouling mechanism	Consitutive Equation	Description	Work reported which used modified Hermia's blocking laws.
Complete blocking	$V = \frac{J_0}{k_{CB}}(1 - e^{-k_{CB}t})$	No particles accummulation. Particles block pores (d$_{particle}$ = d$_{pore}$)	[151]; [118]
Partial blocking	$V = \frac{J_0}{k_{PB}} ln(1 + k_{PB}t)$	Particles accummulation on each other. Particles block pores (d$_{particle}$ = d$_{pore}$)	[152]; [153]; [154]; [155]
Pore constriction	$\frac{t}{V} = \frac{1}{J_0} + \frac{k_{PC}}{J_0}t$	Particles deposition on pore walls. Internal pore diameter decreases (d$_{particle}$ << d$_{pore}$)	[156]; [157]
Cake formation	$\frac{t}{V} = \frac{k_{CF}}{4{J_0}^2}V + \frac{1}{J_0}$	Layers of particles on membrane surface leads to cake formation (d$_{particle}$ >> d$_{pore}$)	[158]; [159]; [160]

Table 7 Mechanisms of membrane fouling in ultra-low pressure UF system (modified from Peter-Varbanets et al. [121]).

Fouling mechanism		Process
Deposition	Formation of fouling layer	Advective transport
Structural changes	Physico-chemical interactions	Hydrophobic interactions, adsorption, metal bridge formation
	Formation of heterogeneous structures	Biological processes (growth, degradation)
Irreversible fouling	Pore constriction and narrowing	Adsorption, re-growth on permeate side, base layer

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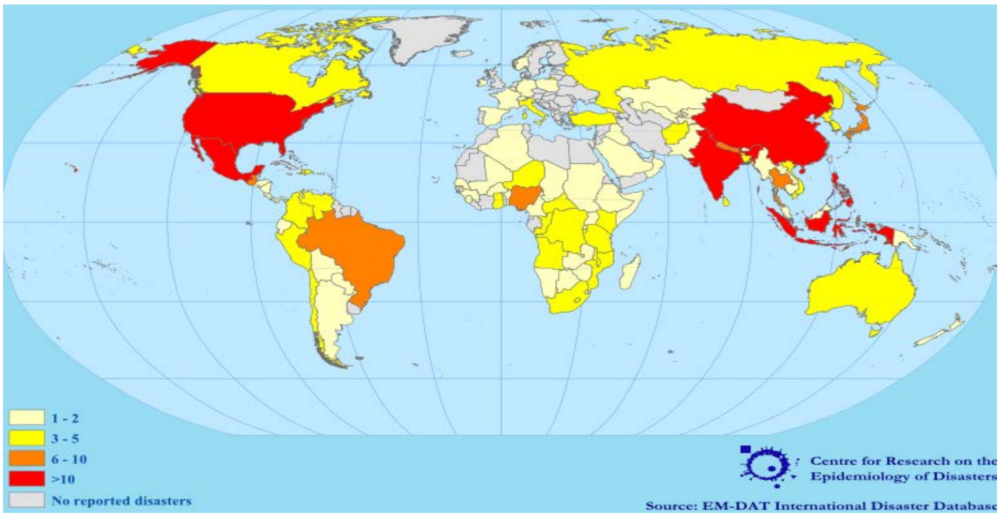

Figure 1 Natural disasters occurrence in 2011 [24].

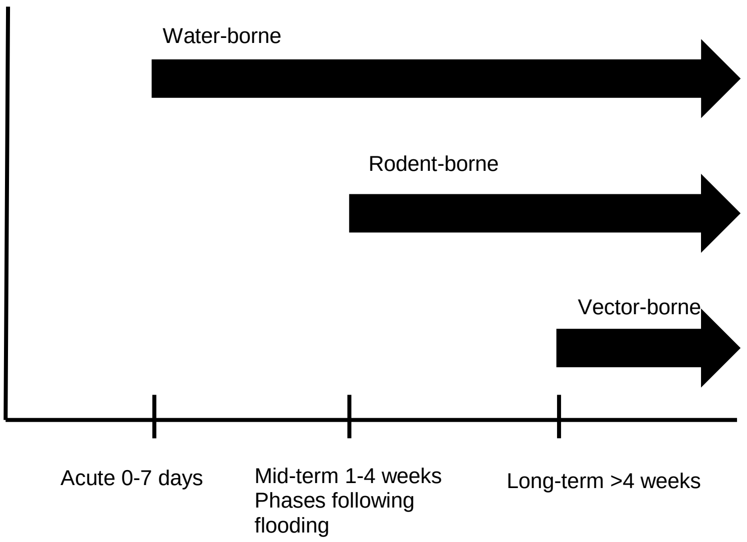

Figure 2 the occurrence of infectious disease outbreaks following floods in relation to time (adapted from Brown and Murray [28]).

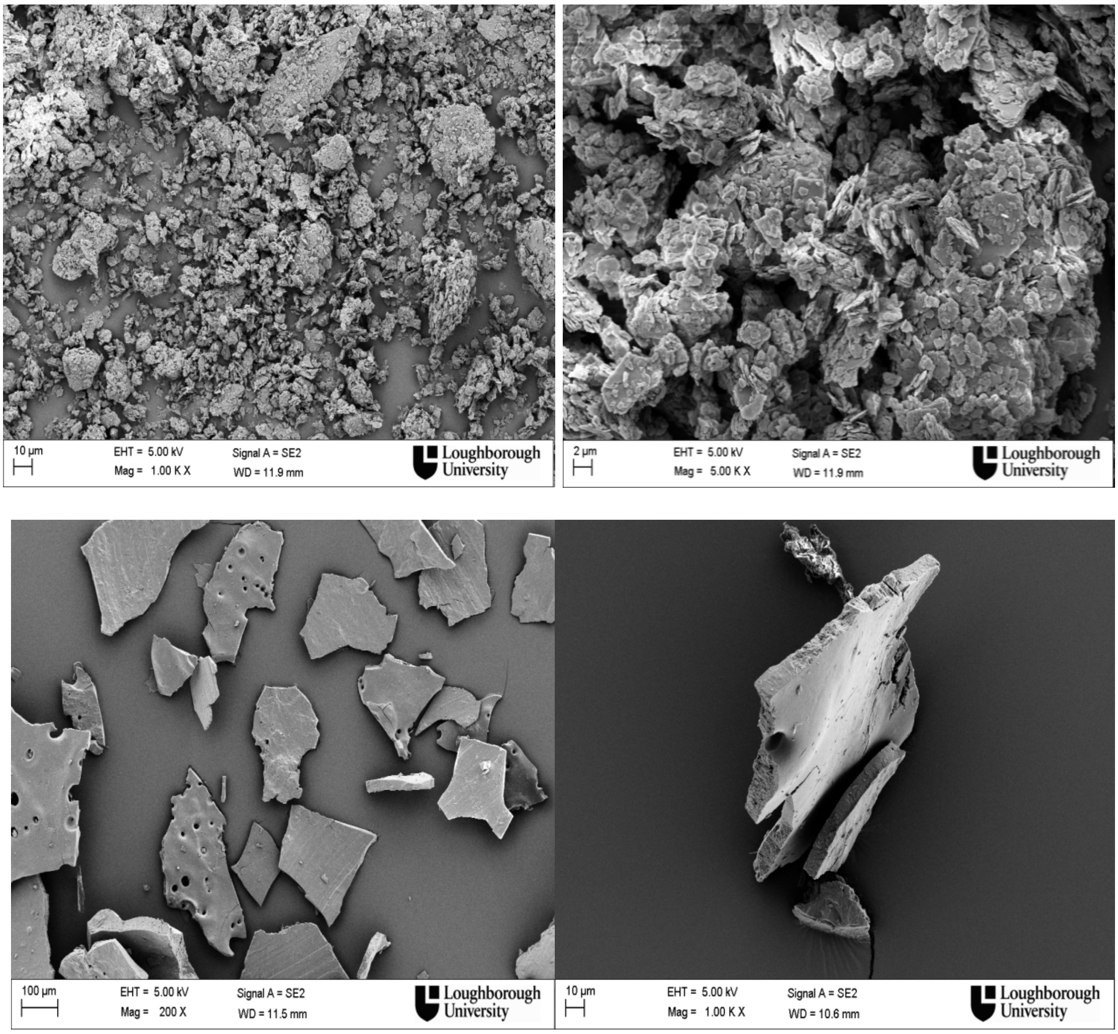

Figure 3 Scanning electron microscope (SEM) pictures of clay particles and humic acid particles (unpublished images collected by authors of this paper).

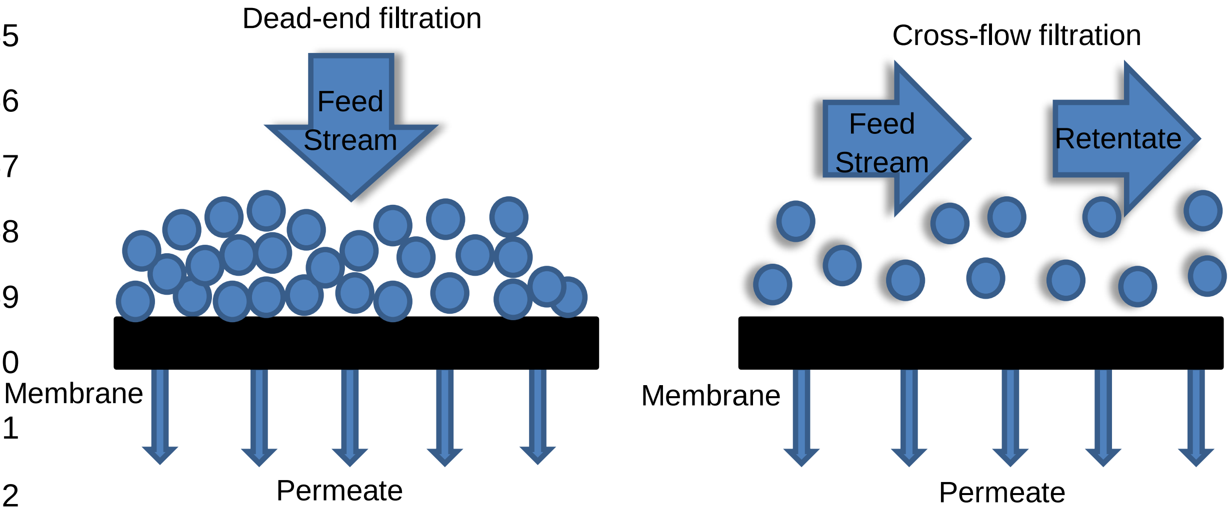

Figure 4 Membrane operational configurations.

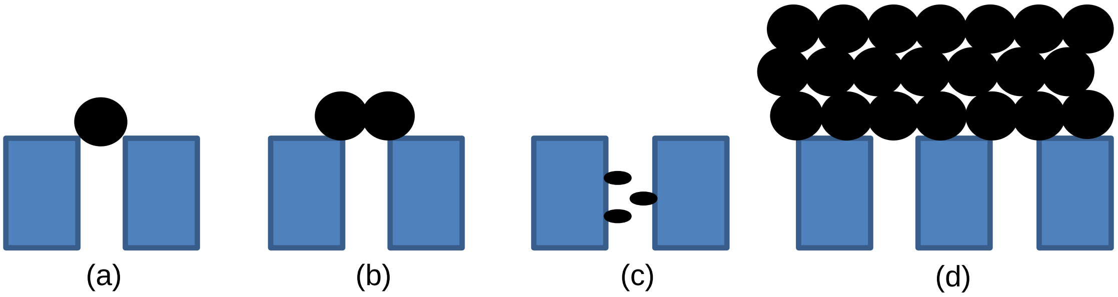

Figure 5 Fouling mechanisms of a porous membrane: a) complete pore blocking, b) partial pore blocking, c) pore constriction (standard pore blocking), and d) cake formation (modified from Field [161]).

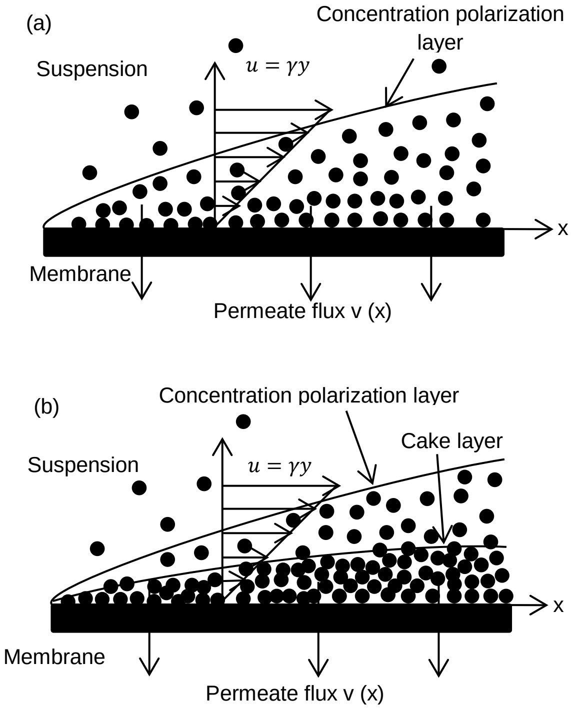

Figure 6 (a) Concentration polarization layer over a membrane surface, and (b) Cake layer between concentration polarization layer and membrane surface (modified from Chen et al. [162]).