Review

Surface water filtration using granular media and membranes: A review

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HIGHLIGHTS

- MF/UF membranes effectively remove bacteria especially after chemical modification.
- After pretreatment to prevent fouling, NF/RO can remove ionic and saline content.
- SSF, or RSF if land use is limited, is recommended for developing countries.
- GAC combined with MF or SSF is a sustainable option for drinking water production.
- Compared to RO, MF/UF with some pretreatment can be a more cost-effective option.

GRAPHICAL ABSTRACT
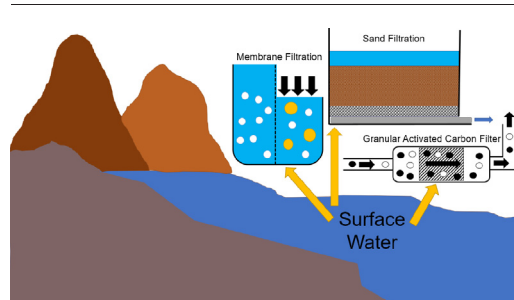
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ABSTRACT

Significant growth of the human population is expected in the future. Hence, the pressure on the already scarce natural water resources is continuously increasing. This work is an overview of membrane and filtration methods for the removal of pollutants such as bacteria, viruses and heavy metals from surface water. Microfiltration/Ultrafiltration (MF/UF) can be highly effective in eliminating bacteria and/or act as pre-treatment before Nanofiltration/Reverse Osmosis (NF/RO) to reduce the possibility of fouling. However, MF/UF membranes are produced through relatively intensive procedures. Moreover, they can be modified with chemical additives to improve their performance. Therefore, MF/UF applicability in less developed countries can be limited. NF shows high removal capability of certain contaminants (e.g. pharmaceutically active compounds and ionic compounds). RO is necessary for desalination purposes in areas where sea water is used for drinking/sanitation. Nevertheless, NF/RO systems require pre-treatment of the influent, increased electrical supply and high level of technical expertise. Thus, they are often a highly costly addition for countries under development. Slow Sand Filtration (SSF) is a simple and easy-to-operate process for the retention of solids, microorganisms and heavy metals; land use is a limiting factor, though. Rapid Sand Filtration (RSF) is an alternative responding to the need for optimized land use. However, it requires prior and post treatment stages to prevent fouling. Especially after coating with metal-based additives, sand filtration can constitute an efficient and sustainable treatment option for developing countries. Granular activated carbon (GAC) adsorbs organic compounds that were not filtered in previous treatment stages. It can be used in conjunction with other methods (e.g. MF and SSF) to face pollution that results from potentially outdated water network (especially in less developed areas) and, hence, produce water of acceptable drinking quality. Future research can focus on the potential of GAC production from

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alternative sources (e.g. municipal waste). Given the high production/operation/maintenance cost of the NF/RO systems, more cost-effective but equally effective alternatives can be implemented: e.g. (electro)coagulation/flocculation followed by MF/UF, SSF before/after MF/UF, MF/UF before GAC.

Contents

1. Introduction

The Earth's surface is around 71% water that is mostly saline. Water is also present in the ground, air and within living organisms (Gleick, 1993). Climate change, population growth and increased urbanization pose huge challenges to water supply systems and place an ever-increasing demand on the finite fresh water resources. The World Health Organization (WHO) estimates that, 844 million people worldwide lack a safe drinking-water service, including 159 million people who are dependent on surface water. The United Nations (UN) Sustainable Development Goal Six calls for countries to ensure universal and equitable access to safe and affordable drinking water by 2030 (Sustainable DG Fund, 2015). Investing in efficient and cost-effective treatment technologies is essential to mitigate against the effect of water scarcity especially in low and middle-income countries. The aim of this paper is to provide a clear and concise overview of current surface water filtration methods, assessing cost aspects and, hence, their applicability to under-developed/developing nations.

1.1. Hydrogeological and natural effects on surface water

Surface water quality is mostly influenced by groundwater and less by surface run-off. During periods of heavy precipitation though, the reverse phenomenon is observed: surface water affecting groundwater quality (McLachlan et al., 2017). All changes to groundwater-surface water relationships increase the likelihood of flooding. For example, extended urbanization increases the surface run-off and hinders the groundwater recharge during precipitation. Moreover, agricultural activity can contribute to the decrease of rainwater storage in the ground. Such phenomena can influence surface water in a complex way that depends on various aspects including crop type, soil type, and climate (Hocking and Kelly, 2016; Han et al., 2017). Due to the variability in geological strata and other factors such as soil type, altitude, ecology supported by a certain water body etc., standards tend to differ. For instance, more natural/background organic content is expected in humic waters than in the non-humic ones. Hence, the allowable dissolved organic carbon (DOC) concentrations vary depending on the specific water type (DEFRA, Government W., 2014).

1.2. Typical problems in surface water

• *Nitrogen (N)*

Nitrogen (N) is present in water mainly in three forms: i.e. ammonium (NH_4^+), nitrite (NO_2^-), and nitrate (NO_3^-). These are parts of the "nitrification chain" with NH_4^+ as the first link and NO_3^- as the last one

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Nomenclature

AC	Activated Carbon
APS	Ammonium Persulphate
AS	Activated Sludge
DO	Dissolved Oxygen
DOC	Dissolved Organic Carbon
DWTP	Drinking Water Treatment Plant
EPS	Extracellular Polymeric Substances
FO	Forward Osmosis
GAC	Granular Activated Carbon
MF	Microfiltration
N	Nitrogen
NF	Nanofiltration
NOM	Natural Organic Matter
PAn	Polyaniline
PCTE	Polycarbonate
PhACs	Pharmaceutically Active Compounds
RO	Reverse Osmosis
RSF	Rapid Sand Filtration
SDG	Sustainable Development Goals
SS	Suspended Solids
SSF	Slow Sand Filtration
TMP	Transmembrane Pressure
TOC	Total Organic Carbon
UN	United Nations
UF	Ultrafiltration
WHO	World Health Organization
WWTP	Wastewater Treatment Plant

before its conversion into nitrogen gas (N_2). Nitrogenous pollutants are significant as they are particularly harmful when ingested; NO_3^-, specifically, is linked to the "blue baby syndrome" that is potentially fatal (Knobeloch et al., 2000).

• *Eutrophication*

Another problem in surface waters is eutrophication. When an excess of nutrients enters a water body, an algal bloom occurs inducing increased consumption of the dissolved oxygen (DO) in the water. This is particularly an issue in still waters such as ponds and lakes. Eutrophication issues are difficult to predict and result from the application of chemical fertilisers, as well as from nutrient leaching and wastewater discharge to surface water (Huang et al., 2017; Glibert, 2017).

Another issue related to eutrophication is the appearance of cyanobacteria in surface water. Responsible for the production and release of oxygen 2.7 billion years ago (Biello, 2009), these micro-organisms can also produce cyano-toxins that are harmful to many higher organisms such as fish, cattle and humans (Álvarez et al., 2017). Thus, it is not only important to treat wastewater discharged to surface water for nutrients, but also to disinfect the water to inactivate bacteria (Rajendran et al., 2018). A common source of municipal, agricultural and industrial water are lakes and reservoirs. These are susceptible to environmental changes as they have low flow velocity; the latter is translated into a decreased natural ability to replenish DO. Eutrophication can thus cause significant issues (Hou et al., 2016). Nutrients and natural organic matter (NOM) can be removed by processes such as activated sludge (AS) and sand filtration, and the microorganisms produced due to the nutrient enrichment can be removed by microfiltration (MF) and ultrafiltration (UF) (Chollom et al., 2017; AWWA, 2017; Bruni and Spuhler, 2012).

• *Heavy metals*

Heavy metal concentrations that generate short-term contamination events in surface water principally originate from anthropogenic activities (e.g. coal burning, mining, pesticide use, battery production and disposal, welding, etc.). Over time, ecosystems usually adapt to coping with elevated heavy metal levels of natural origin (Paul, 2017). Heavy metals and metalloids, especially cadmium (Cd), zinc (Zn), lead (Pb) and Arsenic (As), are of particular concern; once an organism absorbs them, there is no easy excretion. Hence, they end up bioaccumulated in food chains (Cooper et al., 2017; Goretti et al., 2016; Liu et al., 2017; Zhao et al., 2016). Surface water is also heavily affected by industrial effluents. For instance, Howladar (2017) presented a case study in Bangladesh according to which surface water near industrial areas is likely to be contaminated with a variety of pollutants including NO_3^-, phosphates (PO_4^{3-}), heavy metals, As, etc. Specifically, surface water near a coal fired power station was found with PO_4^{3-}, Cd and iron (Fe) concentrations exceeding the World Health Organization (WHO) guidelines. Similarly, Hou et al. (2016) concluded that heavy metal concentrations are expected to be higher in urban rather than rural areas.

Heavy metals and metalloids are commonly removed from wastewater and surface water using granular activated carbon (GAC). However, this can require process optimization to achieve higher/complete removal (Sounthararajah et al., 2015). Forward osmosis (FO) and reverse osmosis (RO) can alternatively be used. A "draw solution" that requires the addition of solute including ammonium bicarbonate (NH_4HCO_3) is used in FO. However, these chemicals need to be removed from the treated water to be considered safe for reuse. Hydraulic pressure is applied in RO, thus causing it to have a higher power consumption than FO (Vital et al., 2018). According to more recent advances,

ultra- and nanofiltration (UF, NF) can also remove some heavy metals and metalloids (Lam et al., 2018; Maher et al., 2014).

1.3. Principles of water treatment

The WHO issues guidelines in contaminant parameters that must be met for a water source to be considered safe and drinkable. It also sets guidelines for the performance of specific parts of a water treatment system. This involves different guidelines for centralised and decentralised systems. Some components of centralised systems are beyond what is achievable in decentralised systems, thus other methods are adopted in decentralised solutions to remove pollution to similar standards (WHO, 2017a).

Water treatment aims at producing water respecting the quality standards that depend on its use after treatment (Lin et al., 2015). In developed countries, surface water is processed in wastewater treatment plants (WWTPs) and drinking water treatment plants (DWTPs) that apply various treatment steps including coarse and fine screening, sedimentation, coagulation/flocculation, various filtration methods, AS, primary and residual disinfection, etc. (L. Yang et al., 2017).

Each method usually targets specific pollutant groups. For example, AS processes remove NOM, NO_3^- and PO_4^{3-} from wastewater (AWWA, 2017; Industries F, 2001; Agency MPC, 2006; Keene et al., 2017). Coagulation and flocculation remove ionic/colloidal material such as clay particles and dissolved metals. Filtration and disinfection are required for the remaining material such as bacteria, viruses and other dissolved metals (Moussa et al., 2017; Sillanpää et al., 2018; Lagaly and Ziesmer, 2003; Su et al., 2017; Mckie et al., 2015; Ebeling et al., 2003; Jeon et al., 2016; Malakootian et al., 2010; Krystynik and Tito, 2017; Tito et al., 2016). For the purposes of producing an insightful and acceptable in length review, the focus from herein will be on filtration (MF/UF, NF/RO, sand filtration) and GAC that target specific pollutants such as heavy metals and metalloids (e.g. Cd, Pb, As, copper (Cu)), and indicator parameters (e.g. total organic carbon (TOC), *E. coli*, oil emulsions, etc.). The methods assessed will be compared as such with the WHO guidelines [WHO, 2017a]. In recent years, each of these methods has been the focus of research. To the best of the knowledge of the authors, however, there is a knowledge gap circa the last 5 years in reviewing all of them. Hence, this work aims at presenting an overview of the MF/UF, NF/RO, sand filtration and GAC systems in terms of efficiency, applicability in developing countries, and cost aspects, always by extracting information from the most up-to-date studies.

2. Membrane filtration methods

Membrane filtration consists of a single layer of material (i.e. membrane) allowing water and potentially a part of the dissolved or suspended material to pass. Specifically, MF, UF and NF can filter out 0.5–5, 0.005–0.5 and 0.0007–0.005 μm particles, respectively. RO can remove almost all contaminants larger than a water molecule (Engineering GP, 2012). Membranes are usually made of woven fibres (Chollom et al., 2017), ceramics (Mouiya et al., 2018), polymeric or metallic materials (Waszak and Gryta, 2016). They can also be modified to improve their performance; for example, decrease fouling (Ko et al., 2018), or increase the removal of specific pollutants (e.g. As) (Chatterjee and De, 2017).

2.1. Micro and ultrafiltration (MF, UF)

MF does not remove the smaller particles that UF and NF can remove. However, it is effective in eliminating bacteria (Chollom et al., 2017). MF can be used in domestic water recycling systems (Manouchehri and Kargari, 2017). Moreover, it can constitute a pretreatment stage before UF, NF or RO (Gwenaelle et al., 2017), thus reducing the possibility of fouling in following steps (i.e. UF/NF/RO) since it removes potential foulants (i.e. bacteria) (Jamaly et al., 2014).

If the MF flux is to be kept constant, then transmembrane pressure (TMP) is to be augmented as the resistance of the fouling cake across the filter becomes increasingly influential with time. Therefore, it is necessary to backwash or clean the filters when they become overly fouled (Gwenaelle et al., 2017). Table 1 presents the main findings of several studies investigating the performance of MF/UF systems applied for the removal of organic pollutants such as oil and algae.

Table 1 is indicative of the major research that has been conducted regarding MF/UF and the parameters they can remove from water (NOM is the principal one); impressive if not complete retention results have been noted [e.g. (Suresh and Pugazhenthi, 2017; Suresh et al., 2016; Monash and Pugazhenthi, 2011)]. Materials used for the MF membranes include ceramics, metals and woven fabrics that can be modified with different materials (e.g. titanium dioxide (TiO_2) nanoparticles or polyvinylpyrrolidone) to increase characteristics such as hydrophilicity and disinfection (Carpintero-Tepole et al., 2017; van der Laan et al., 2014). As shown in Table 1, recent research has indeed pushed towards the direction of MF/UF membranes impregnated with materials to enhance their performance [e.g. (Suresh and Pugazhenthi, 2017; Carpintero-Tepole et al., 2017; Monash and Pugazhenthi, 2011)]. It can be also observed that most of the membrane materials involve relatively intensive procedures for the membrane production (e.g. (Suresh and Pugazhenthi, 2017; Suresh et al., 2016; Monash and Pugazhenthi, 2011)). For instance, ceramics require several heating processes, with high temperatures (i.e. ≥600 °C), as well as compaction. Woven membrane production requires the use of machinery and/or skilled labour. Moreover, it is possible that chemical additives are needed to improve the filtration characteristics. These factors are no issue in more developed nations where electrical supply, skilled labour and chemical deliveries are in relative abundance. However, this cannot always be the case in less developed countries (Peter-Varbanets et al., 2009). Membranes, particularly of woven fibre, can be fragile and expensive. Further research is required into producing cheaper and more durable MF/UF membranes that can be synthesized and implemented for longer filtration times in countries under development (Mecha and Pillay, 2014). Further research can also be conducted in the domain of MF/UF coatings applied for disinfecting or fouling-reducing purposes (Mecha and Pillay, 2014; Pi et al., 2016). In terms of compliance with the WHO standards, it can be concluded that MF/UF can effectively remove organic material from wastewater (e.g. (Suresh and Pugazhenthi, 2017; Carpintero-Tepole et al., 2017)). However, partial removal or even reduction of the size of organic particulates was also reported in some cases (e.g. (Carpintero-Tepole et al., 2017; Suresh et al., 2016)). More importantly, most of the cited studies do not assess the MF/UF capability to remove inorganic pollutants such as heavy metals/metalloids (e.g. (Hung and Liu, 2016; Suresh et al., 2016; Monash and Pugazhenthi, 2011)). Hence, it can be suggested that MF/UF is an effective pre-treatment process preceding other treatment steps such as NF/RO, SSF or GAC filtration.

2.2. Nanofiltration (NF) and reverse osmosis (RO)

NF is used to remove larger solutes than RO. In terms of size of removed contaminant, it lies between UF and RO; NF is effective at removing particles between 100 and 1000 Da in size (Sutherland, 2009; Li et al., 2013). Nevertheless, NF membranes can foul quickly due to their small pore sizes unless sufficient pre-treatment steps (e.g. coagulation, MF) are undertaken (SAMCO, 2017). Compared to RO, NF is less effective at filtering ions from water, but more cost-effective as lower TMPs are required to produce the same permeate flow of water (Yorgun et al., 2008). For certain contaminants (e.g. pharmaceutically active compounds (PhACs)), NF generally shows greater removal capability than UF (Yoon et al., 2007). UF, NF and RO can all be chemically adjusted to improve the removal of specific contaminants. For instance, it was found that increasing the solution pH from 4 to 10 increased the removal of arsenates (AsO_4^{3-} or As(V)), arsenites (AsO_3^{3-} or As(III)), chromates (CrO_4^{2-}), and perchlorates (ClO_4^{-}). On the contrary, increasing the solution conductivity produced the opposite phenomena (Yoon et al., 2009).

RO is the membrane process that removes ions from water by providing hydraulic pressure to overcome the osmotic pressure, thus reversing the natural flow of water towards the more concentrated solution. Therefore, this process requires energy to generate the pressure required to overcome osmotic pressure. Furthermore, pre-treatment of the feed water through other processes (e.g. MF, NF) is needed to remove bacteria, viruses and larger ions that are likely to generate RO fouling problems (American Membrane Technology Association (AMTA), 2009; Blanco-Marigorta et al., 2017).

Recent advances in the RO treatment include the introduction of forward osmosis (FO) as an added improvement. Being a natural process, it does not require any energy input. Hence, it can greatly decrease the amount of applied pressure required in the RO step to overcome the osmotic pressure difference (Bartholomew et al., 2017). The FO membrane can be partially self-cleaning with the fouling material being simply sheared off by flow. Even in this case however, fouling gradually occurs and membrane replacement/remediation is still required. For this reason, combatting FO fouling by operating at a higher cross flow velocity has been suggested (Lotfi et al., 2017). Especially for desalination purposes, FO membranes can be applied with wastewater as the feed solution and seawater as the draw solution; this results in diluting the seawater, as well as in water recovery from wastewater (Kim et al., 2018). Research is also needed particularly with regard to draw solutes; inorganic draw solutes are among the least researched in this field (Qasim et al., 2017).

The RO performance is influenced by various parameters. For example, membrane permeability depends on temperature and the difference between hydraulic and osmotic pressure. During desalination, initial salt concentrations along with temperature significantly impact on the final salt rejection, thus affecting the quality of produced RO effluent (Shaaban and Yahya, 2017; Monnot et al., 2017). Furthermore, greater pressure is connected with higher water recovery (Roy et al., 2017). However, if pre-treatment and membrane coatings are used, poor RO membrane performance due to fouling can be prevented (Wu et al., 2017; Y. Zhang et al., 2017). Table 2 shows the removal of ionic material by RO and NF.

According to the results reported in Table 2, RO/NF can remove ionic material to an impressive extent [e.g. (Víctor-Ortega and Ratnaweera, 2017; Vatanpour et al., 2017; Masindi et al., 2017)]. It can also be noted that most of the implemented membranes are made of polyamide (i.e. non-woven polyester fabric membranes coated in monomers) [e.g. (Víctor-Ortega and Ratnaweera, 2017; Baudequin et al., 2011; Boddu et al., 2016)]. These membranes are thin and fragile produced through interfacial polymerisation. Given that they can be damaged after contact with free chlorine radicals, using them after disinfection is ill advised ((Association) MRW; Hydranautics, 2001). Another observation resulting from Table 2 is that RO is not an impenetrable barrier to ionic material. Even though >95% retention rates are attained [e.g. (Vatanpour et al., 2017; Liu et al., 2008)], complete retention of target pollutants is hard to achieve [e.g. (Bi et al., 2016; Hedayatipour et al., 2017)]. Moreover, it can be seen that As(V) is more easily removed than As(III), probably due to physical changes in As(III). This could be the case for other elements such as iron (Fe(II) and Fe(III)) at different oxidation states in RO (Víctor-Ortega and Ratnaweera, 2017). Further research is required into these phenomena to better understand them.

RO/NF membranes require certain technical chemical knowledge and involve complicated production processes. In addition, training and expertise is important to run the RO/NF processes due to their sensitivity to environmental factors such as temperature, pollutant concentration, etc. As previously discussed, RO can be used in conjunction with FO to recover water from wastewater streams. Nevertheless, the latter is not a priority in developing countries that majorly focus on the production of drinking water. MF, UF and other granular filter media remove

Table 1

Overview of studies on the performance of MF/UF systems implemented for the removal of specific pollutants.

Filter material	Filter production	Pollutant	TMP	Filtration configuration	Main findings & observations	Source
Ceramic	Clay powders mixed with polyvinyl alcohol; membrane modified with titanium dioxide (TiO$_2$) nanoparticles	200 mg L^{-1} crude oil	69-207 kPa	Cross-flow MF	• 93–100% rejection of oil emulsion: ceramic support • 99–100% rejection of oil emulsion: ceramic support modified with TiO$_2$ • TiO$_2$ increased hydrophilicity & flux across the membrane • High oil retention: effective removal of TOC • No assessment of biological parameters or other (inorganic) contaminants	(Suresh and Pugazhenthi, 2017)
Anodisc	Anodised alumina	10–30% oil emulsion	25-100 kPa	Dead-end filtration MF	• Complete retention: effective TOC removal • no assessment of biological parameters or other (inorganic) contaminants	(Carpintero-Tepole et al., 2017)
Polycarbonate (PCTE)	PCTE membrane modified with polyvinylpyrrolidone to enhance hydrophilicity	10–30% oil emulsion	25-100 kPa	Dead-end filtration MF	• Partial TOC removal • Larger oil particles broken into smaller particles • No assessment of biological parameters or other (inorganic) contaminants	(Carpintero-Tepole et al., 2017)
Cellulose acetate	Sartorius AG cellulose acetate membrane	10–30% oil emulsion	25-100 kPa	Dead-end filtration MF	• No retention but oil particle size reduced • Filter not satisfying WHO guidelines on organic/inorganic contaminants	(Carpintero-Tepole et al., 2017)
Hydrophilic mixed cellulose ester membrane	Corning cellulose ester filter membrane	10 mg L^{-1} Chlorella sp. (algae); polymethylmethacrylate 10–40 mg L^{-1}	20, 40, 60 kPa	Cross-flow MF	• Presence of Polymethyl methacrylate (PMMA) particles increased algal cake porosity & reduced its compressibility • Lesser final flux possibly due to algal cake compression by drag forces • No assessment of organic/inorganic contaminants	(Hung and Liu, 2016)
Ceramic	80 wt% fly ash	50–200 mg L^{-1} oil emulsion	69-345 kPa	Dead-end MF	• 80–85% rejection for 50 mg L^{-1} oil emulsion (decreasing with increasing pressure) • 92–99.94% rejection for 200 mg L^{-1} oil emulsion (decreasing with increasing pressure) • No assessment of inorganic contaminants	(Suresh et al., 2016)
Ceramic	70 wt% fly ash	50–200 mg L^{-1} oil emulsion	69-345 kPa	Dead-end MF	• 68–82% rejection for 50 mg L^{-1} oil emulsion (decreasing with increasing pressure) • 87–96% rejection for 200 mg L^{-1} oil emulsion (decreasing with increasing pressure) • No assessment of organic/inorganic contaminants	(Suresh et al., 2016)
Ceramic	14.5 wt% Kaolin; 17.6 wt% clay	50–200 mg L^{-1} oil emulsion	69-35 kPa	Dead-end MF/UF	• 93–96% rejection for 50 mg L^{-1} oil emulsion (decreasing with increasing pressure) • 71–86.5% rejection for 200 mg L^{-1} oil emulsion (decreasing with increasing pressure) • No assessment of organic/inorganic contaminants	(Monash and Pugazhenthi, 2011)
Ceramic	14.5 wt% Kaolin; 17.6% clay; modified with TiO$_2$	50–200 mg L^{-1} oil emulsion	69-35 kPa	Dead-end MF/UF	• 97–99% rejection for 50 mg L^{-1} oil emulsion (decreasing with increasing pressure) • 84–92% rejection for 200 mg L^{-1} oil emulsion (decreasing with increasing pressure) • No assessment of organic/inorganic contaminants	(Monash and Pugazhenthi, 2011)

Table 2
Overview of studies presenting the efficiency of RO and NF for the removal of ionic material.

Filter material	Filter production	Pollutant	TMP	Filtration configuration	Pollutant removal	Source
Polyamide	Filter TW30–4040 (DOW corporation)	• As(III): 100 µg L^{-1} • As(V): 100 µg L^{-1}	1.5 MPa	Cross-flow RO	• As(V): ≈100% • As(III): 77–81% after 1st filtration; 95% after 2nd filtration • Almost respecting WHO guideline after 1st filtration; <WHO benchmark after 2nd filtration	(Víctor-Ortega and Ratnaweera, 2017)
Polyamide	SG1812C-28D RO spiral membrane	Firefighting water; fluorinated surfactant: 20 mg L^{-1}	2 MPa	Cross-flow RO	Fluorinated surfactant: 99.9% fluoride concentration < WHO benchmark	(Baudequin et al., 2011)
Polyamide	XLE Filmtec	Swimming pool water; haloacetic acid: 100 µg L^{-1}	0.69 MPa	Cross-flow RO	Haloacetic acid: 80–100%	(L. Yang et al., 2017)
Cellulose acetate	SB50 TriSep	Swimming pool water; haloacetic acid: 100 µg L^{-1}	0.69 MPa	Cross-flow RO	Haloacetic acid: 50–100%	(L. Yang et al., 2017)
Polyamide	XLE Filmtec	Domestic grey water; NaCl: 50 mg L^{-1}	0.69 MPa	Cross-flow RO	NaCl:77–85%	(Boddu et al., 2016)
Amine-functionalized thin-film	Interfacial polymerisation (modified with multiwalled carbon nanotube)	NaCl: 2000 mg L^{-1}	1.5 MPa	Cross-flow RO	NaCl: 95–97.2%	(Vatanpour et al., 2017)
RO thin-film	Espa 2 (Hydranautics)	• NO$_3$: 15.5 mg L^{-1} • NH$_4$: 9.53 mg L^{-1}	1.5 MPa	Cross-flow RO	• NO$_3$: 97.4% • NH$_4$: 90.8%	(Häyrynen et al., 2009)
Polyamide	BW30 (Filmtec)	• Ca: 451.2 mg L^{-1} • Cl: 81.6 mg L^{-1} • SO$_4$: 1101.7 mg L^{-1}	0.5–2.5 MPa	Cross-flow RO	• Ca: 99% • Cl: 96–99% • SO$_4$: 98–100%	(Liu et al., 2008)
Polyamide	SS-NF1–2540: RisingSun Membrane	• NaCl: 100 mg L^{-1} • MgSO$_4$: 100 mg L^{-1}	0.414–0.828 MPa	Cross-flow NF	Up to 60%	(Bi et al., 2016)
Polyamide	JCM-1812-50N by JCM	• Na: 14,864 mg L^{-1} • Ba: 209 mg L^{-1} • Ni: 6.2 mg L^{-1} • TDS: 61,500 mg L^{-1} • Cr: 5.3 mg L^{-1}	0.758 MPa	Cross-flow NF	• Na: 79.6% • Ba: 85.3%; >WHO benchmark; additional treatment needed • Ni: 77.4%; >WHO benchmark; additional treatment needed • TDS: 56.3% • Cr: 58.5%; >WHO benchmark; additional treatment needed	(Hedayatipour et al., 2017)

larger contaminants (e.g. microbes and extracellular polymeric substances (EPS)) and can produce water of acceptable quality for drinking (Suresh and Pugazhenthi, 2017; Carpintero-Tepole et al., 2017; Hung and Liu, 2016; Ortega Sandoval et al., 2017).

As far as the WHO guidelines are concerned, it is seen in Table 2 that NF/RO can remove most forms of pollution to a good degree (e.g. (Víctor-Ortega and Ratnaweera, 2017; Baudequin et al., 2011)). In some cases, though, the produced effluent failed to meet the WHO guidelines for water quality (e.g. (Hedayatipour et al., 2017)). However, such cases typically deal with highly polluted industrial water, the concentrations of which are unlikely in most natural environments.

Finally, it was previously analysed that pre-treatment (e.g. MF) is usually an indispensable step before RO to decrease the possibility of fouling. In this concept, RO is often a needless and costly addition to properly designed DWTPs for countries under development. RO applicability is generally high in areas that need high-quality water for industrial processes, or in places where sea water is the source of drinking and sanitation water (Bogler et al., 2017).

3. Granular media

3.1. Slow sand filtration (SSF)

SSF has been used for around 150 years as a relatively simple and easy-to-operate process that allows raw water to pass through a sand medium. As the water passes through the sand, solids, microorganisms and heavy metals (e.g. Cu and chromium (Cr)) are removed. A bacterial community gradually forms a layer (called 'schmutzdecke') and preys upon bacteria present in the water (Bruni and Spuhler, 2012; Alvarez et al., 2008; Muhammad, 1998). However, SSF requires large areas per unit volume of water treated. Thus, it is either undesirable or even ruled out in densely populated areas or areas where land is expensive (Husiman and Wood, 1974). The latter makes SSF an option mostly suited to rural communities rather than large towns or cities. Other major issues with filters used for SSF include low flow rate as well as their requirement for a certain maturation period before they are available for use (up to 40 days). Unlike other filters that can be restored to use quickly after cleaning, SSF filters need time for the schmutzdecke to regrow (Schmidt, 1977).

A range of different factors can affect the performance of SSF. For instance, caffeine, oestrogens and other PhACs contained in the influent can negatively impact on the ability of the schmutzdecke to remove bacteria (D'Alessio et al., 2015). Influent salinity can also display an inverse relationship with organic content removal (Khengaoui et al., 2015). Excessive suspended solids (SS) can also clog the filters, thus reducing their ability to convey water. Heavy metal removal, specifically, is expected to be improved under conditions of higher total organic content (TOC) in the influent, greater depth of sand and lower flow velocity (Muhammad, 1998).

3.2. Rapid sand filtration (RSF)

RSF is a physical filtration process. Unlike SSF, RSF produces no significant biological layer. Hence, it requires prior and post treatment stages to remove pathogenic substances and prevent fouling. It constitutes a common treatment process for the SS removal in urban areas where land use needs to be optimized and continuous electrical supply is accessible (Management SS and W, 2012). The typical design of a water treatment plant involves several RSFs to allow for one or more to be "offline" for backwashing purposes. Consequently, some filters must deal with a higher flow during backwashing compared to the flow when no backwashing is occurring. This "flow surge" can then lead to increased particle concentrations in the effluent (Han et al., 2009). Additionally, the quality of sand in a RSF deteriorates over the course of years due to the

adsorption of organics and inorganics on the surface of sand granules (Marín, 1992).

The removal of inorganics (e.g. such as Fe, manganese (Mn)) in RSFs is achieved through homogenous, heterogeneous and biological oxidation. Heterogeneous and biological oxidation that mainly occur on the surfaces of granular material since contaminants either adsorb to filter media or are oxidised by microbes attached to the granular matter. Homogenous oxidation occurs in the supernatant and water phase in the filter (Vries et al., 2017). Table 3 shows sand filters in addition to modifying agents that have been applied to enhance their ability to remove trace contaminants (e.g. As). These contaminants can exist in several different oxidation states (in aqueous state), some of which are more easily removed than others (e.g. As(V) and thallous cation (Tl(I)) when compared to As(III) and thallic cation (Tl(III)), respectively) (Gude et al., 2018; Huangfu et al., 2017).

Table 3 shows that sand filtration can be improved in terms of heavy metal removal by means of additives such as Fe or Mn oxides, or polyaniline (PAn) [e.g. (Huangfu et al., 2017; Smith et al., 2017; Eisazadeh et al., 2013)]. Virgin sand shows some ability to remove trace metals that can be toxic or carcinogenic [e.g. (Chaudhry et al., 2017)]. However, this ability can be significantly improved for even small concentrations of trace heavy metals by the coating of sand with Fe or Mn oxides. These metal-based additives increase the surface area and adsorption capabilities of sand media (Wang et al., 2009). The results in Table 3 show that modifying the sand filters to reduce harmful heavy metals such as Pb and Cr can be achieved simply. Additionally, sand filters (SSF in particular) can be easily managed using local skills; only basic training is needed to operate them (Smith et al., 2017). Hence, sand filtration can constitute a sustainable water treatment option for developing countries. Nevertheless, it shall be noted that sand filtration shows mixed results with regards to the WHO guidelines. In few cases, the remaining contaminant concentration meets the WHO guidelines (e.g. (Chaudhry et al., 2017)); these typically involve additives such as Fe or Mn. The mixed results suggest that sand filtration should be used in conjunction with another treatment method to ensure the removal of heavy metals/metalloids.

3.3. Granular activated carbon (GAC)

Activated Carbons (ACs) currently used in water treatment are made of a variety of materials (e.g. nutshells, wood, coal and petroleum) (Arena et al., 2016). Moreover, they differ in terms of characteristics (e.g. number of micro and macro-pores, surface area, functional groups etc.) (De Silva, 2000). GAC is commonly used as a filtration or post filtration method to adsorb organic/taste/odour compounds, synthetic organic chemicals and PhACs with results that depend on the carbon quality, pollutant type and concentration. When used for post filtration, GAC receives high-quality water to adsorb organic compounds that were not filtered out in previous stages. If applied as filters, GACs often replace or are combined with RSFs, thus reducing the need for further filtration. GAC filters can operate at higher loading rates than SSF. Therefore, they are popular in treatment plants where space is a limiting factor (EPA US, 2011; Shanmuganathan et al., 2017). Furthermore, GAC can be added to the anaerobic digestion process to improve methane production. It can also enhance the sludge digestion process by increasing the removal of SS (including volatile SS) (Y. Yang et al., 2017; J. Zhang et al., 2017; Al Mamun et al., 2016).

When the lifecycle of a GAC filter is discussed, it is uncertain how long it will take before it becomes saturated with target pollutants. Some target pollutants will saturate the GAC filter quicker than others (Zietzschmann et al., 2016). Biological activity is observed in GAC; this has beneficial effects such as further removal of NOM. However, this can also generate problems such as clogging, anaerobic/dead zones and detachment of microbes from the GAC. In the initial stages, GAC removes NOM through adsorption. As the process progresses, a biofilm

Table 3

Overview of studies presenting the removal of trace inorganics using sand media. Additives were implemented to improve removal.

Target pollutant	Additive to sand media	Operating conditions (flow rate, temperature, concentration, etc.)	Main findings	Importance	Source
As	Sand preloaded with drinking water/As(III) & drinking water/NH$_4^+$ & drinking water/Mn (II) & drinking water/As(III) & groundwater	• Flow rate: 1 m h^{-1} • Column diameter: 90 mm • Height: 1 m • Filter: 0.5 m quartz sand (0.4–0.8 mm) • Supernatant: 10 cm (drinking water); 2 cm increasing to 15 cm due to clogging before backwashing (aerated groundwater)	• Preloaded NH$_4^+$ column: almost complete removal of NH$_4^+$ indicating conversion to NO$_3^-$ • No significant differences seen in influent & filtrate of Mn and As(III) preloading • As (III) preloaded sand beds immediately oxidised As(III) to As(V); virgin sand beds took 22 days for total oxidation of As (V)	As(V) more negatively charged than As(III) at neutral pH; thus, more easily removed by adsorption processes	(Gude et al., 2018)
As	Fe	• Bucket capacity: 80 L • Gravel (5–13 mm) depth: 7 cm • Finer gravel (3–5 m) depth: 3 cm • Washed sand (2 mm) depth: 30 cm • Unwashed sand (<2 mm) depth: 5 cm • 2 cm Fe nails added in various configurations: beneath unwashed sand & above sand in diffuser basin	• Biosand filters effectively removed As; 81% removal decreasing to 50% after 5 months; As concentration only once below 50 μg L^{-1}, this >> WHO benchmark (10 μg L^{-1}) • Fe addition to sand filter; As removal: 86–95% (As concentration consistently<50 μg L^{-1}); however; hovering just above the WHO benchmark; additional treatment needed	As can be removed very simply after the Fe addition to the sand filters; despite not meeting the WHO benchmark, method significantly reducing As concentration in contaminated areas	(Smith et al., 2017)
Trace Tl (I) & Tl(III)	Dosing of MnO$_2$ colloids at the same time as Tl input	• Flow rate: 3.18m^3 m^{-2} h^{-1} • Diameter: 18 mm • Height: 300 mm • Quartz sand: d = 3 mm • Temperature: 25 °C • Initial concentration of Tl(I) & Tl(III): 0.5 μg L^{-1}	• The higher the MnO$_2$ concentrations, the higher the removal of both Tl(I) & Tl(III) • Tl(I) removal more effective; Tl(III) more stable forming complexes in water • Quartz sand alone unable to remove Tl	Tl is highly toxic even at low concentrations; thus, Tl removal via the addition of MnO$_2$ to sand filtration can be useful during the WWTP operation	(Huangfu et al., 2017)
Pb(II)	Fe	• Flow rate: 0.764m^3 m^{-2} h^{-1} • Diameter: 20 mm • Height: 250 mm • Quartz sand: 0.15 mm (average) • Temperature: room temperature • Initial Pb(II) concentration: 38.14 mg L^{-1}	• 80% removal at pH = 4; remaining concentration: 7.62 mg L^{-1} >> WHO benchmark • 99% removal at pH = 11; remaining concentration: 0.39 mg L^{-1} > WHO benchmark; additional removal required • Fe coating improved Pb(II) removal • Bed depth also increased Pb(II) removal	Pb water pollution is an issue in areas with old piping; hence, especially in countries under development	(Eisazadeh et al., 2013)
Pb(II)	PAn composites	• Flow rate: 0.764m^3 m^{-2} h^{-1} • Diameter: 20 mm • Height: 250 mm • Quartz sand: 0.15 mm (average) • Temperature: room temperature • Initial Pb(II) concentration: 38.14 mg L^{-1}	• 57% removal at pH = 4; >WHO benchmark; additional removal required • 68.8% removal at pH = 11; >WHO benchmark; additional removal required • PAn coating improved Pb(II) removal • Bed depth also increased Pb(II) removal	See above	(Eisazadeh et al., 2013)
Cr(VI)	MnO$_2$	• Diameter: 0.106–0.125 mm • Temperature: 25 °C • pH: 6 • Cr(VI) concentration: 500 μg L^{-1}	95.12% adsorption of Cr(VI) after 60 min with a MnO$_2$ dose of 8.9 mg L^{-1}; remaining Cr(VI) concentration: 24.4 μg L^{-1} < WHO benchmark	Cr(VI) is a carcinogen found in naturally contaminated groundwater, as well as in anthropogenically polluted surface water	(Chaudhry et al., 2017)
As & Cu	Activated bauxsol coating (produced as in (Genç-Fuhrman et al., 2005))	• Particle size: 0.5 mm • Temperature: 22 °C • pH: 6.5	Almost complete As & Cu removal	Significant As & Cu water contamination due to acid mine drainage & industrial activities	(Genç-Fuhrman et al., 2007)

grows, and NOM is removed by combined adsorption and biodegradation (Shanmuganathan et al., 2017).

According to the results reported in Table 4, GAC is a rather versatile filtration material that can reduce various forms of pollution. It can generally be used and produced in relatively simple ways to remove remaining organics such as viruses and pesticides even in developing communities (e.g. after a gravity sand filter) (Guo et al., 2017; Kårelid et al., 2017; Aqsolutions, 2016). The major queries with these materials is their ease of production and replication in different areas, as well as their ability to surely meet WHO guidelines (e.g. (Monnot et al., 2016; Mazarji et al., 2017; Abudalo et al., 2013)). As seen in Table 4 [e.g. (Abudalo et al., 2013; Enniya et al., 2018)], a common modification of AC to improve heavy metal removal is impregnation with acids, typically nitric (HNO_3) or orthophosphoric acid (H_3PO_4) (Abudalo et al., 2013; Guo et al., 2017). As discussed before, chemical modification in this way is achievable in places where chemicals can be synthesized, transported, and stored easily. However, the latter is rarely sustainable in developing countries (Aqsolutions, 2016). Whilst the more complex ACs used in developed nations can remove heavy metals and other contaminants [e.g. see Table 4: (Kårelid et al., 2017; Katsigiannis et al., 2015)], ACs implemented in less developed areas can be used in conjunction with other methods (e.g. MF and SSF) to face pollution that results from the outdated water network [e.g. see Table 4: (Guo et al., 2017)] and, finally, produce water that is of acceptable drinking quality.

4. Cost aspects of surface water filtration

4.1. Centralised and decentralised systems

With the focus on rural, remote areas of middle/low-income countries where the provision of drinkable quality is a major issue, two ideas are mainly suggested and compared upon their applicability. The first includes a decentralised water treatment system using ceramic MF/UF and GAC filters. The second idea is about a more conventional, centralised DWTP, which applies multiple treatment stages (screening, sedimentation, chemical coagulation/flocculation, filtration, disinfection).

A decentralised system is a configuration of locally produced ceramic microfilters and carbon filters to treat raw surface water. Several current projects are based on this concept. For instance, the PureMadi project where silver ceramic pot filters are used to remove pathogens and viruses from water (PureMadi, 2014). The Aqsolutions biochar filter system is another example where gravel, sand and biochar filters are used to remove SS, pathogens, viruses and harmful chemicals (Aqsolutions, 2016). The capital costs of ceramic filters used in decentralised systems range from $2 to $40, with the majority of them typically costing between $2 and $5 (Plappally and Lienhard, 2012). The average yearly cost of running a ceramic and biochar water filtration system is estimated at $0.74 per m^{-3} of treated wastewater (Guo et al., 2018; Gwenzi et al., 2017; Jirka et al., 2013; Mohan et al., 2014).

Typically, centralised systems are considered as more cost-effective. They are usually developed in areas of higher population density where the distance between treatment plants and consumers is limited. However, such systems are not always economical in rural and distant areas, since pumping water over long distances is difficult and expensive (Plappally and Lienhard, 2012). Furthermore, it shall be noted that the predominant energy-consuming process in drinking water treatment is the distribution/conveyance step. It has been reported that domestic water distribution can reach up to 50% of the total energy expended during the whole water treatment process (Kate and Shuming, 2017). Moreover, installing various smaller conventional DWTPs in remote agricultural communities is likely to be an unsustainable option due to lack of transportation and energy infrastructure that can ensure the continuous DWTP supply. In addition, smaller facilities tend to produce water with a higher cost per unit of treated water compared to the larger ones (Copeland, 2017).

A partially gravity-fed sand/biochar filter system can be constructed to serve a remote community, with colloidal silver-ceramic filters at the point of use to remove any remaining bacteria, thus eliminating the need for an expensive disinfection step. It is in the opinion of the authors that such a system can constitute a viable "semi-centralised" alterantive for a rural community. It can combine the benefit of a centralised system (i.e. reduced cost per unit of treated water) with the advantage of decentralised systems where pumping is not required for the water distribution. More importantly, the suggested sand/biochar filter system is cheap and simple; it can be constructed using local materials and operate with gravity. However, it cannot account for areas where desalination is required; RO is needed in such cases.

The calculation of the energy used for water treatment is a highly complex issue, with the average energy requirements of conventional DWTPs reported to range between 0.29 and 1.3 kWh m^{-3} (Kate and Shuming, 2017; EEA, 2014). If sophisticated treatment is needed (e.g. desalination via RO), the average energy consumption of a plant can raise up to 3 kWh m^{-3}, though (Bartels and Andes, 2013). The range of energy requirements mentioned previously is quite wide mainly due to the local, global and temporal differences in the prices of drinking water production and transportation (Copeland, 2017). Therefore, it is difficult to construct a single effective universal benchmark relating energy requirements and cost regarding drinking water production. Hence, case studies on different environments and settlement types are suggested as necessary further work. This is outside the scope of this review which is targeted at the water quality that can be achieved using various filtration technologies with regards to the WHO guidelines. More specific information on the operational costs of filtration and granular media technologies follows.

4.2. Operational costs for the MF/UF, NF/RO, sand filters and GAC systems

Table 5 provides indicative information on the operational costs of the MF/UF, NF/RO, SSF, RSF and GAC technologies. The direct comparison among the different cited studies is not straightforward due to the variability of a number of factors including plant capacities, experimental assumptions and the scale of each study. Nevertheless, general conclusions can be drawn.

Table 5 shows that in areas where viruses and ionic contamination is not the primary treatment target, a system employing solely MF/UF can provide effluents of acceptable quality by being more cost-effective than one employing both MF/UF and NF/RO. It is also worth noting that there are alternative (and cheaper) methods for the removal of ionic contamination from water, typically coagulation/flocculation. These are reported to remove high amounts of most heavy metals with aluminium (Al), Fe or biopolymer coagulants considered the best for removal. According to recent technological advances, electro-coagulation using scrap metals is an effective treatment option (Mckie et al., 2015; Ebeling et al., 2003; Malakootian et al., 2010; Krystynik and Tito, 2017). MF/UF and coagulation/flocculation present lower operational costs compared to RO. However, RO remains a necessity in areas where seawater is the water source.

Additionally, granular media can be used and modified with adsorbents. These can be applied for the removal of harmful ions in water before or after a MF/UF phase. SSF can remove a vast amount of pollution in one step when compared to other methods such as MF/UF, NF/RO and RSF. Nevertheless, it does have the drawback of relatively high capital cost and land requirements (Center for Disease Control and Prevention (CDC), 2014). Despite the latter, cheap and simple operation render SSF an interesting option for countries under development. RSF can also be applied in developing areas. However, the backwashing required to keep the filter media clean introduces extra difficulties (compared to SSF); pumps are possibly needed. Finally, GAC filters are a more sophisticated filtering method that can remove most groups of pollutants, possibly after some modification. The challenge now is to produce

Table 4

Overview of studies presenting the removal capability of GAC implemented for specific pollutants.

Target pollutant	GAC material	Operating conditions (flow rate, temperature, concentration, etc.)	Main findings	Importance	Source
Turbidity, DOC, UV$_{254nm}$	Bituminous coal	• GAC bed height: 0.95 m • Bed diameter: 0.08 m • Media volume: 4.8 L • Empty bed contact time: 13–20 min • Average linear velocity: 3–4.5 m h^{-1} • Bed porosity: 0.4	• Turbidity removal>88% • DOC removal>72% • UV$_{254nm}$ removal>64% • Uncertain whether this material can completely satisfy the WHO guidelines	GAC was used in this study to mitigate RO membranes biofouling	(Monnot et al., 2016)
NO$_3^-$	Coconut shell char modified with NaOH	• GAC bed height: 0.2 m • Bed diameter: 0.01 m • Bed volume: 0.019 L • Empty bed contact time: 9.5mins • Flow rate: 2 mL min^{-1} • Average linear velocity: 1.53 m h^{-1} • Temperature: 25 °C • Initial NO$_3^-$ concentration: 10 mg L^{-1}	• 80% removal • Initial NO$_3^-$ concentration already<WHO guidelines; however, high removal indicative of material's potential to meet WHO guidelines regarding NO$_3^-$	NO$_3^-$ are significant pollutants in surface water due to agricultural, industrial & domestic activities	(Mazarji et al., 2017)
Cu(II)	GAC produced from bituminous Calgon MRX-POX, modified with 20% HNO$_3$ & impregnated with carboxybenzotriazole	• Bed diameter: 4.86 mm • Bed depth: 120 mm • Average linear velocity: 0.873 m h^{-1} • Empty bed contact time: 8.24mins • Initial Cu Concentration 31.8 mg L^{-1}	• 105 mg Cu adsorbed g^{-1} of adsorbent • No detectable Cu concentration in effluent for up to 400BV • Cu WHO benchmark: 2 mg L^{-1} • Data suggesting that material highly effective at Cu removal and during useful life	Cu(II) more easily recovered by GAC & modified GAC than traditional methods (e.g. flocculation/coagulation)	(Abudalo et al., 2013)
Cr(VI)	GAC produced from apple peel & impregnated with H$_3$PO$_4$	• Batch experiment • Stirring speed: 400 rpm • Contact time: 2 h	• 18.78 mg Cr(VI) adsorbed g^{-1} of adsorbent	Cr(VI) is a carcinogen present in groundwater, but also in surface water due to anthropogenic activity	(Enniya et al., 2018)

Table 4 (continued)

Target pollutant	GAC material	Operating conditions (flow rate, temperature, concentration, etc.)	Main findings	Importance	Source
Cr(VI)	GAC produced from calcinated egg shell & modified with wheat bran	• Temperature: 28 °C • Initial Cr(VI) concentration: 10–50 mg L^{-1} in 10 mg L^{-1} steps • Batch experiment • Stirring speed: 180 rpm • Contact time: 5 h	• Results suggesting that WHO can be met under provision of correct dosage • 96.96% removal; remaining Cr concentration: 0.304 mg L^{-1} > WHO benchmark: 0.05 mg L^{-1} • Note: very high initial Cr concentration, rarely seen in the environment	See above	(Renu et al., 2017)
Pb(II)	GAC produced from *Phragmites australis* reed & impregnated with K_2SiO_3, H_3PO_4 & humic acid	• Temperature: 35 °C • Initial Cr concentration: 10 mg L^{-1} • Batch experiment • Stirring speed: 120 rpm • Contact time: 12 h	160 mg of Pb(II) g^{-1} of adsorbent after 30mins	Pb(II) a significant issue in areas with old water pipe networks, or where poor industrial waste management practices occur	(Guo et al., 2017)
PhACs including: Codeine, Diclofenac, Tramadol, etc.	GAC: Aquasorb 5000/Jacobi	• Temperature: 30 °C • Bed diameter: 150 mm • Bed depth: 1000 mm • Empty bed contact time: 60 mins • Supernatant: 400-500 mm • Average linear velocity: 6.2 m h^{-1}	Overall PhAC removal>99%.	PhACs are a significant issue in modern societies where drugs can be potentially bio-accumulated if not removed from wastewater streams	(Kårelid et al., 2017)
Atenolol (ATL)	GAC oxidised by Ammonium Persulphate (APS) & sulfuric acid	• Batch experiment • Adsorption time: 12 h • APS concentration increased from 0.5 mol L^{-1} to 2.5 mol L^{-1} • Shaking speed: 250 rpm • Temperature: 25 °C	• ATL adsorption capacity increased from 40 mg g^{-1} to >90 mg g^{-1} of adsorbent for APS concentration from 0.5 to 2 mol L^{-1} • ATL adsorption capacity dropped for a higher APS concentration of 2.5 mol L^{-1} • After 2 h: ATL adsorption capacity stabilized at 85 mg g^{-1} of adsorbent for 2 mol L^{-1} of APS	See above	(Song et al., 2017)
Ibuprofen (IBU), Triclosan (TCS), Naproxen (NPX), Bisphenol-A (BPA), Ketoprofen (KFN)	GAC: Filtracarb CC60	• Bed width: 50 mm • Bed depth: 40 mm • Initial IBU concentration: 2 μg L^{-1} • Average linear velocity: 3.1 m h^{-1} • Number of columns in series: 4 • Removal percentages measured after 5th day of operation	Removal percentage after: • 1st column: BPA > 50%; TCS: 60%; IBU:30%; NPX > 35%; KFN:40% • 2nd Column: BPA: 75%; TCS: 85%; IBU > 55%; NPX: 65%; KFN: 60% • 3rd Column: BPA: 95%; TCS > 95%; IBU > 85%; NPX: 90%; KFN > 90% • 4th Column: BPA: 100%; TCS: 100%; IBU: 95%; NPX > 95%; KFN > 95%	See above	(Katsigiannis et al., 2015)

Table 5
Operational cost for the MF/UF, NF/RO, sand filters and GAC systems.

Filtration method/membrane	Operational cost (£)	Contaminants removed	Source
MF/UF	0.02 $ m^{-3} for a plant capacity of 20,000 m^3 day^{-1} 0.1–0.15 $ m^{-3} for a plant capacity of 20,000 m^3 day^{-1} (after running the optimization model)	SS, dissolved solids, bacteria (including pathogens), viruses, organic material	Dore et al. (2013) Bick et al. (2012)
NF/RO	0.68 $ m^{-3} for a plant capacity of 30,000 m^3 day^{-1} 0.5 $ m^{-3} by using modern desalination techniques	SS, dissolved solids, bacteria (including pathogens), viruses, organic material, ions	Banat Energy and Capital (2009)
SSF	0.001 $ m^{-3} assuming filtering 0.04 m^3 day^{-1} for 10 years SSF followed by chlorination for rainwater treatment in airports: total monthly cost = 1.05 $ m^{-3}; 60% < price paid to water supply company	SS, dissolved solids, bacteria (including pathogens), viruses, organic material, some metallic material (after modification)	Center for Disease Control and Prevention (CDC) (2014) Moreira Neto et al. (2012)
RSF	0.05 $ m^{-3} for a 15-year operation 0.02 $ m^{-3} for a pilot-scale RSF performing tertiary treatment of municipal wastewater	SS, dissolved solids, bacteria	Sanchez et al. (2012) Heinonen-Tanski et al. (2003)
GAC	0.31 $ m^{-3} for a plant of 300,000 population equivalents 0.13 $ m^{-3} for a pre-industrial scale system enabling the reuse of industrial laundry effluents with a feed of 360 m^3 d^{-1}	SS, dissolved solids, bacteria (including pathogens), viruses, organic material, some metallic material (with modification)	Mulder (2015) Ciabattia et al. (2009)

GAC from discarded materials that will be of adequate quality for water filtration, thus decreasing the cost of the GAC implementation.

5. Areas for further research

Taking under consideration the UN Sustainable Development Goals, research is now to focus on the production of drinking water in developing nations. Currently, much research seeks to improve the capabilities of already known materials for removing contamination. However, research is expected to start focusing on making these materials a sustainable option for developing nations. Hence, Sustainable Development Goal 6 (i.e. "ensure access to water and sanitation for all") shall be achieved in countries under development, too. As it is currently, materials produced in the lab are often difficult to fabricate in developing nations as they require expertise and technology that is not available there (Sustainable DG Fund, 2015; WHO, 2017b) This paper shows that SSFs and biochar are two potentially accessible technologies that can push towards the direction of Goal 6.

SSFs are a well-established method of drinking water treatment that have been commercially used for nearly 150 years. Therefore, research gaps emerge when new parameters/standards are adopted regarding water quality. Sands have been coated with substances such as Fe and NH$_4^+$ compounds to improve the removal of NOM and As(V) as discussed in Section 3.2. However, SSF in conjunction with other media such as GAC constitutes a research gap. The GAC insertion in a SSF system can increase the surface area of pores, potentially improving its capacity to remove pollution.

Biochar is receiving increasing international attention due to its potential to remove carbon from the atmosphere. Moreover, it can also sequester pollution such as heavy metals, organic and inorganic compounds from air and water through adsorption. Compared to GAC, it contains larger amounts of macro-pores that allow greater levels of biological action (Huggins et al., 2016). However, most studies report biochar production at high temperatures. Little has been published regarding biochar produced by municipal waste. Furthermore, biochar production at lower temperatures has been viewed as less favourable due to its lower capacity of pollution removal compared the high-temperature chars. Nevertheless, new technologies that make low-temperature char a viable option are currently under research (Aqsolutions, 2016). Additionally, materials such as wood and nut shells have been extensively researched with regards to biochar production (Chen et al., 2016). The content of most municipal waste, though, includes organics, plastics, and papers that contain either few or none of the currently desired compounds in biochar feedstock (Group WB, 2012). Therefore, more research is required on non-wooden organic feedstock for biochar.

6. Conclusions

The pressure for sustainable use of the limited surface water resources is constantly increasing. Hence, this work examined the efficiency, applicability and cost of different filtration and membrane methods used for the removal of various pollutants such as bacteria, viruses, heavy metals and metalloids. The following major conclusions were reached:

- MF/UF can effectively remove bacteria and/or act as pre-treatment before NF or RO, thus reducing the possibility of fouling in these consequent steps. The materials used for MF/UF membrane production often involve intensive procedures. MF/UF membranes can also undergo modification (e.g. with TiO$_2$ nanoparticles) to improve their performance. Nevertheless, these aspects can raise an issue in less developed countries where energy, trained workforce and provision of chemicals can be in limited availability.
- NF/RO show high removal capability with contaminants such as PhACs and ionic material. However, NF membranes are prone to fouling unless sufficient pre-treatment (e.g. coagulation, MF) occurs. Similarly, pre-treatment (e.g. MF, NF) is required to avoid RO fouling problems. More importantly, RO is a necessity in areas where sea water is used for drinking/sanitation purposes. Considering that they require high level of technical expertise as well as sophisticated methods of production/maintenance, NF/RO systems are possibly an unnecessarily expensive option for areas where drinking water production is the priority. MF/UF and granular media can be used instead.
- SSF can be simply and easily operated for the removal of solids, microorganisms and heavy metals. However, extended large areas per unit volume of water treated are needed. In urban areas where the available space is limited, RSF can be alternatively applied along with a certain prior and post treatment to prevent fouling. Coating the sand filters with metal-based additives (e.g. Fe or Mn) is a relatively easy process that can significantly increase their adsorption potential. Therefore, sand filtration is recommended for use in developing countries.
- GAC adsorbs organic compounds that were not filtered out in previous treatment stages, especially in WWTPs where land use needs to be optimized. Combined with other methods (e.g. MF and SSF), GAC can constitute a cost-effective way to produce water of acceptable drinking quality in less developed nations.
- Current research gaps include the detailed investigation of the performance of integrated systems such as SSF operation in conjunction with GAC. Moreover, future research can focus on the production of GAC from the content of municipal waste.
- In terms of cost, MF/UF is a more cost-effective option compared to RO

when viruses and ionic contamination are not the principal target pollutants. If ionic pollution remains an issue, (electro)coagulation/flocculation can be used as less costly but satisfactorily effective treatment alternatives before a MF/UF step.

Considering the current challenges in the developing world regarding sustainable development, this paper shows that mankind currently does possess the required knowledge to achieve the UN Sustainable Development Goals for 2030. Accessible drinking water for all, as well as access to adequate sanitation and hygiene are within reach due to the recent advances in pyrolysis procedures. These make biochar an increasingly viable option for water treatment. Cheap and easy to operate SSF combined with biochar can provide drinking water to millions, as well as adding biochar to sewage can improve basic sewage treatment processes. Research is therefore needed in how to produce and use the current state-of-the-art filtration materials in a developing world setting.

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