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Renewable energy-powered membrane technology in Tanzanian communities

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Dissolved contaminants such as ions or organic matter require advanced technology for effective removal. Technologies such as membrane processes are to date absent in remote areas of developing countries, in part due to the absence of a reliable electricity grid to power such technologies, but also due to the large distances to be served in remote areas. By directly coupling a nanofiltration system with solar energy, the energy provision and storage obstacle can be resolved. Here, two very challenging natural waters were treated to drinking water standard without requiring permanent infrastructure: both water samples had very high concentrations of fluoride (50–60 mg/L), while one of them also had a high total organic carbon content (255 mg/L). In both cases the WHO guideline value of 1.5 mg/L for fluoride was achieved with the chosen membrane. The solar irradiance provided an unsteady power source, which did not impact on water quality in a significant manner. Given the somewhat extreme characteristics of the source waters, making such waters potable effectively increased the available water quantity. The technical feasibility of such a solar-powered ultrafiltration and nanofiltration hybrid system was demonstrated in terms of produced drinking water quantity (1200 L per solar day), water quality and specific energy consumption. While such state-of-the-art technology offers great potential towards the provision of clean water in rural areas, the remaining obstacles for effective implementation of such technologies are predominantly non-technical.

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INTRODUCTION

Supply of clean drinking water remains a challenge in many regions of the world. Even though the Millennium Development Goal (1990–2015, ref. [1]) to halve the number of people without access to 'improved sources of water' was largely achieved, many regions remain without access to clean water. This is particularly the case in (i) arid regions, (ii) remote areas and (iii) locations where the available water is contaminated. Notably, one target of the Sustainable Development Goals (2015–2030, ref. [2]) is to provide 'clean, accessible water for all', which will require a substantial effort to treat chemically contaminated water in remote areas.[3] With increasing world population, industrial development and climate change, both water scarcity and pollution are bound to increase. This poses a significant challenge particularly in rural areas, where a lack of infrastructure and electricity combined with large distances render common treatment options difficult and expensive.[4,5]

For this purpose, decentralized treatment systems such as renewable energy-powered membrane filtration, which can be operated without infrastructure, provide an ideal solution.[4,6,7] Membrane filtration is an established technology in seawater desalination, water reuse and surface water treatment. Significant market uptake has made cost of membranes plummet in the past decade. Similarly, solar energy (photovoltaics (PVs)), driven initially by large subsidies, has now become an affordable source of clean electricity. The costs to produce potable water with such 'leapfrog' technologies are well within the costs of untreated water sold in developing countries.[4,8] Nevertheless, this market uptake is lagging in developing countries, and in remote areas it is virtually absent. The reasons for this include the relatively low confidence of aid organizations, for example, in advanced technologies, operation and maintenance issues, as well as a general lack of experience in successfully deploying membrane systems in areas where trained staff and support structures are not yet available.

Turning water that is not fit for consumption into potable water will be able to alleviate water stress in many regions, especially if less energy-intensive methods than seawater desalination can be employed. Membrane technologies that are suitable for such applications are ultrafiltration (UF), where the removal of microorganisms or turbidity is required.[9–12] This technology will be suitable to alleviate the many lives that are claimed by water-induced diarrhoea. Nanofiltration (NF) is able to remove macro-molecules such as humic substances as precursors to disinfection by-products, as well as many inorganic dissolved contaminants such as arsenic (As), fluoride (F) and uranium (U) that cause a number of severe health issues [8,13–17] and micropollutants such as pharmaceuticals and pesticides.[18–20] Reverse osmosis (RO) is suitable for seawater desalination in that it can retain monovalent ions.[21] Significant drawbacks of seawater RO are the energy requirements that can be improved by using waters with lower salinity and remineralization requirements.[22] Such waters are surface or groundwaters, as well as potentially wastewater effluents.

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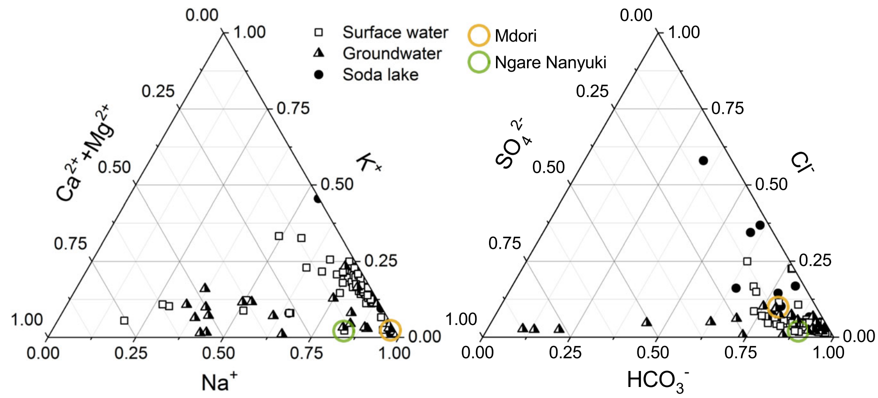

Fig. 1 Ternary plot showing the water composition. The Na–K–(Ca + Mg) ternary plot is shown on the left, and the HCO_3–SO_4–Cl plot on the right

Table 1. Water quality of the Mdori and Ngare Nanyuki waters, sampled during the field trials on 1 March 2014 and 19 March 2014, respectively

Coordinates	Mdori S03°47.273′, E035° 51.138′	Ngare Nanyuki S03°10.929′, E036° 51.676′
Altitude (m)	971	1450
pH (−)	10.5	8.3
Conductivity (μS/cm)	4920	3530
Turbidity (NTU)	0.3	1.5
Inorganic carbon (mg/L)	469	395
Total organic carbon (mg/L)	3	255
Dissolved organic carbon	2	249
UV absorbance 254 nm (mg/L)	0.1	11.7
SUVA (L/mg.cm)	5.4	4.7
Fluoride (mg/L)	58	53
Calcium (mg/L)	0.5	12
Sodium (mg/L)	1479	948
Chloride (mg/L)	277	152

While in urban areas water reuse is an alternative, the water consumption in rural areas of developing countries is often incomparable to urban areas of developed countries. In consequence, managing wastewater quality and quantity requires alternative treatment approaches. Treating brackish water that is available in many regions of water scarcity is a good option that is often accompanied by dissolved contaminants such as arsenic or fluoride. Surface water, which in many regions may be more contaminated due to inadequate sanitation or wastewater treatment in general, is a common source. Regional variation in rainfall pattern and associated turbidity or organic matter loading may be significant.[23,24]

In this work, the performance of a renewable energy-powered membrane system (UF-NF) was studied with two real waters that were selected from many groundwater and surface water samples collected in remote Tanzanian communities. The aim of this research was to investigate, with real waters and on site in remote communities, the (i) impact of energy fluctuations induced by the renewable energy resource (the sun) on water quality; (ii) removal of fluoride in carbonaceous waters and (iii) implications of high organic matter content on water quality. Further, community response to such an advanced treatment intervention was observed.

RESULTS

Water quality

Two waters were selected from a survey of >200 water sources in northern Tanzania based on physico-chemical water quality. A map of the sample area and field site selection is presented in subsection 'Field test site selection and location'. The ternary diagram analysis in Fig. 1 identifies a unique water type, namely bicarbonate–alkaline, for the majority of samples. Typically, alkaline lava and ash contain high contents of silicate minerals and glass. Groundwaters, particularly those containing dissolved CO_2, react readily with alkaline silicate to release sodium and bicarbonate ions.[25] The presence of bicarbonate and sodium ions exerts a positive influence over the fluoride concentration. Some groundwaters, on the other hand, are the sulphate–alkaline–earth type, which may have a negative impact on fluoride concentration due to the limiting factor of calcium.

For the field trial, two carbonaceous waters with very high fluoride concentrations were chosen and the water quality is summarized in subsection 'Field test site water quality: Mdori and Ngare Nanyuki'. The 'Mdori' water is a hot spring where water rises up naturally through a borehole at a temperature of about 70 °C. The 'Ngare Nanyuki' water is a surface blackwater originating from a swamp with similar water characteristics in terms of fluoride, pH and salinity with the addition of a high natural organic matter concentration. The sampling area and field test sites are shown in Fig. 8 and water quality is summarized in Table 1. The reason to focus on these two waters was that the water quality of these waters is almost identical with the main difference being a low organic matter content of the 'Mdori' water and a very high organic matter content of the 'Ngare Nanyuki' water. It was anticipated that this very high organic matter content may pose additional challenges and impact on fluoride retention mechanisms.

PV-powered membrane system

The waters were treated in the field using a directly coupled (no batteries) PV-powered UF-NF system [26,27] as depicted at the two field test sites in Fig. 2. The system description can be found in the subsection 'Renewable energy-powered membrane system set-up and operation'. For these field experiments, system operation was conducted with actual solar irradiance occurring in February and March 2014. Results of two days were selected: 28th February for Mdori and 21st March for Ngare Nanyuki. For a given natural solar irradiance variation, system performance parameters—motor

Fig. 2 Renewable energy-powered system at the field test sites (left) Mdori, Babati Rural District of the Lake Manyara Region and (right) Ngare Nanyuki, Arumeru District of the Arusha Region with water sources underneath (photos © Schäfer)

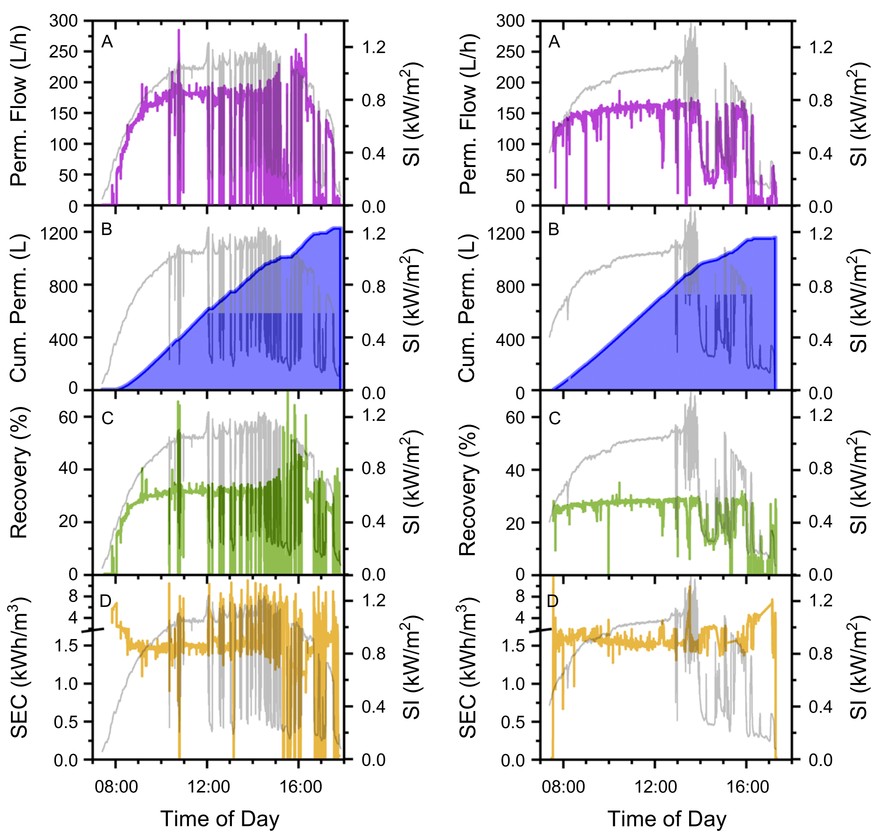

Fig. 3 System performance results for the NF90 membrane in Mdori (left, **a**–**d**) and Ngare Nanyuki (right, **a**–**d**) waters

power, pressure, feed flow, flux, cumulative permeate volume, recovery and specific energy consumption (SEC)—are datalogged as a function of time (in 1-s intervals) throughout the solar day. Furthermore, the permeate quality in terms of electrical conductivity (EC), as well as fluoride, inorganic carbon and organic carbon (Ngare Nanyuki water only) concentrations, plus retention are examined, while pH and temperature are monitored. No other dissolved contaminants were established to be a concern in these waters. The results are presented in Figs. 3 to 5.

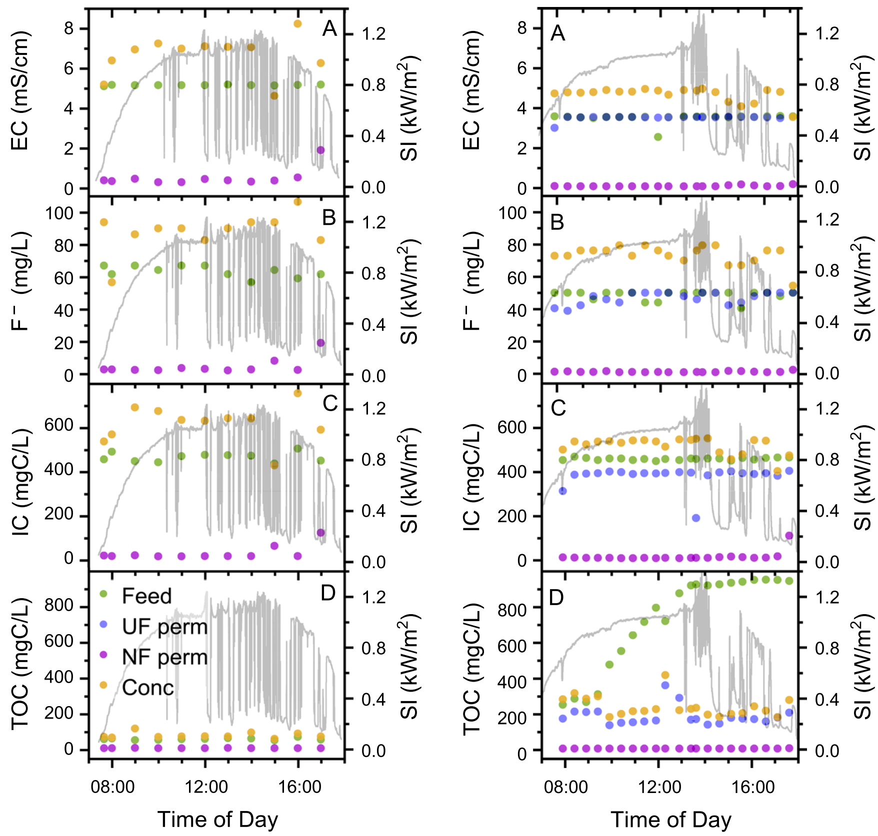

Fig. 4 Water quality as a concentration of fluoride, electrical conductivity, inorganic carbon and total organic carbon obtained with NF90 in Mdori (left, **a**–**d**) and Ngare Nanyuki (right, **a**–**d**) waters

Impact of energy fluctuation on permeability and cumulative water quantity

Results of the water permeability of the membranes and the resulting water volume produced over a solar day are shown in Fig. 3 for the NF90 membrane. This membrane was chosen based on previous results, where NF90 exhibited the best permeability while achieving drinking water quality from these quite extreme fluoride concentrations.[26]

As can be seen in the results, the weather conditions during the individual days at both sites were naturally different. The solar irradiance in Mdori (Fig. 3, left) indicates a generally fine day with some heavy-but-passing cloud in the afternoon. These clouds affect the permeate flow (A) and later in the day reduce the contribution to the cumulative volume produced (B). Overall, about 1200 L of water were produced throughout this day at a recovery of about 30% (C) and SEC of about 1.5 kWh/m^3 (D). The clouds alter the driving force (transmembrane pressure) and hence the recovery, which results in a SEC fluctuation.

In Ngare Nanyuki (Fig. 3 right), the sky was clear until 13:00, at which time some light cloud appeared, followed by a period of heavy cloud cover between 14:00 and 15:10. Nevertheless, the system performance remains very similar, with the main difference being a slightly lower permeate flow (A), which results in a cumulative permeate volume just under 1200 L (B). The recovery of about 25% (C) results in a SEC of about 1.5 kWh/m^3 (D). This is remarkably similar in both water despite the slightly lower salinity (measured as EC) of the Ngare Nanyuki (3530 µS/cm) as compared to the Mdori (4920 S/cm) water and the very high total organic carbon (TOC) of the Ngare Nanyuki water (255 mg/L). What is not accounted for in the SEC calculation is the energy required for air bubbling to maintain UF permeate flux in this extreme water. The power consumption of the air bubbler is 130 W, which is significant compared to the ~245 W typically drawn from the PV panels for powering the pump during periods of good performance (SEC~1.5 kWh/m^3). Assuming a worst-case scenario, then the continuous operation of the air bubbler requires an additional SEC of 0.8 kWh/m^3. While the air flow rate (120 L/min) was effective in mitigating fouling of the UF membrane, the flow rate has not been optimized and thus it remains to be determined if a lower power bubbler (with a lower air flow rate) could would still be effective. This water was the only water to date where such bubbling was required, which can be explained by the extreme concentration. Implications will be discussed in the subsection 'Organic matter removal'.

Impact of energy fluctuation on water quality

The water quality results obtained by treating these two waters are summarized in Fig. 4 (left: Mdori; right: Nares Nanyuki) as contaminant concentration for the feed, UF permeate, NF permeate and concentrate. UF permeate was not sampled in Mdori due to the very low TOC concentration, assuming that no retention of solutes by UF would take place. With the high TOC concentration in Ngare Nanyuki, the UF permeate that was sampled as an impact of TOC on retention of other solutes was anticipated.

The water quality achieved in Mdori Fig. 4 (left) in terms of EC (A) indicates that the NF permeate has a consistent EC well below 500 mS/cm, with an increase at the end of the day where solar irradiance reduces and more salt diffuses across the membrane. Given that very little permeate is produced, this is normal and of little impact for overall water quality (cumulative data not shown). The conductivity results obtained with the inline EC sensor (not included) confirms the water quality variability with irradiance in detail. Fluoride (B) is right on the WHO guideline value of 1.5 mg/L. While the F concentration also increases during periods of low

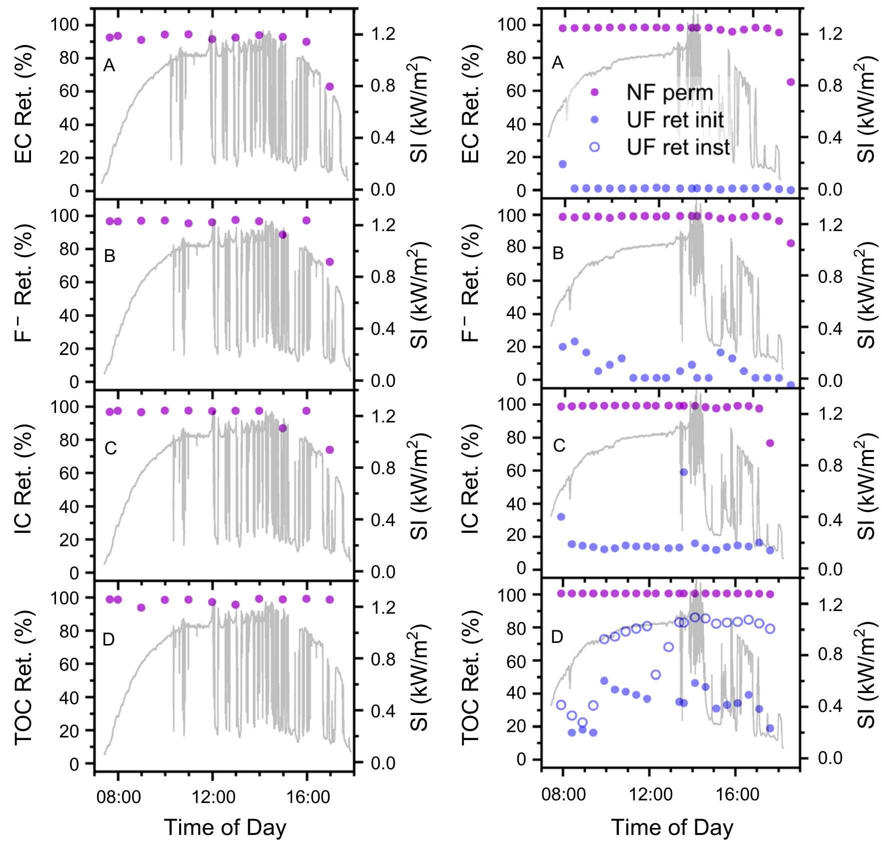

Fig. 5 Solute retention by UF and NF (NF90) for Mdori (left, **a**–**d**) and Ngare Nanyuki (right, **a**–**d**) waters

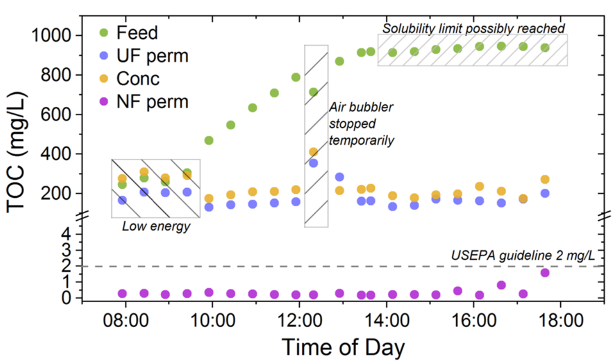

Fig. 6 Challenges with organic matter removal with the Ngare Nanyuki water

solar irradiation, the cumulative F concentration is below the limit (data not shown), because of the low water volume produced during these periods. The inorganic carbon (C), which is of no health concern, again follows this trend, while the little TOC in the Mdori water (D) was removed to very low NF permeate concentration. The concentrate concentration reflects the removal with increases in concentration. Those values were measured from samples taken, rather than determined by mass balance calculations.

The permeate quality from Ngare Nanyuki (Fig. 4, right) is marginally better than that of the Mdori water. EC (A) is mostly <100μS/cm and fluoride <1 mg/L with an increase at the end of the day due to low power available. Feed and UF permeate show very similar concentrations, indicating no major association of fluoride with the organic matter retained by the UF. Inorganic carbon (C) appears lower in the UF permeate which may be related to the bubbling in the feed tank. Increased concentrate concentrations reflect that EC, F and IC are retained by NF, as expected.

Most interesting is the TOC concentration (D). The NF permeate is collected outside the system for consumption by villagers, the concentrate is discarded and the feed tank is continuously refilled with fresh water. The permeate TOC is well below 0.5 mg/L for most of the day, reduced from 255 mg/L. Due to the very high retention of TOC by the NF membrane, the concentration in the tank increases rapidly over the course of the day until a saturation is reached just below 1000 mg/L. This 'saturation' is caused by a deposition of organic matter on the membrane and possibly a precipitation of organics. This is evidenced in that the UF permeate concentration is unaffected by this increase over the course of the day. While organic matter removal is discussed in more detail in the next section.

UF and NF retention data are shown in Fig. 5, Mdori (left) and Ngare Nanyuki (right). The UF and NF retention is calculated using permeate concentration and feed concentration. In the case of TOC, two different retention values are reported, namely 'UF ret init', which is the retention calculated with the initial feed concentration and 'UF ret inst', which is calculated with the actual concentration in the feed tank. The Mdori water shows consistently high retention >90% for EC (A), fluoride (B), IC (C) and TOC (D). Due to diffusion and a declining dilution effect, the salt retention decreases at the end of the day, while TOC retention is unaffected, which emphasized steric exclusion. The Ngare Nanyuki water shows a marginally higher NF retention that degrades towards the end of the day due to low solar irradiance. UF retention of EC (A) is nil, while fluoride (B) indicates a declining retention of <20% that is likely to be attributable to experimental error more so than the anticipated affiliation of organic matter with fluoride. UF retention of IC (C) is elevated and probably

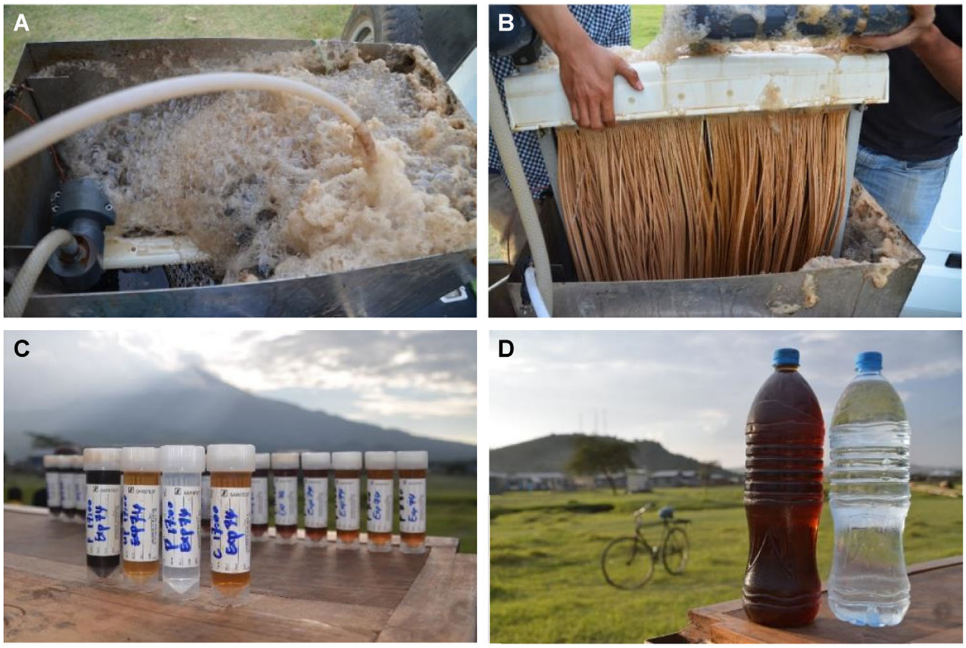

Fig. 7 Organic matter removal in Ngare Nanyuki: **a** foam development in feed tank, **b** organic matter deposition on UF hollow fibre membranes, **c** samples at the end of the day: feed tank, UF permeate, NF permeate and concentrate and **d** feed and product water (© Schäfer)

related to the air- bubbling hat that is required for this water for fouling control in the UF process, resulting in gassing out of IC in the feed tank. TOC retention (D) is very high in NF, while UF retains 20–80% of TOC. The higher values are obtained when considering the concentration in the tank, the lower values when the feed concentration is used. This can be explained with some of natural organic matter occurring in colloidal form and such macromolecules and colloids attaching to the UF membrane surface. Such deposition as well as intense foaming were observed and are described in detail in the next section.

Organic matter removal

Closer examination of the organic matter concentration in the Ngare Nanyuki water reveals some relevant information in terms of membrane fouling and TOC removal (see Fig. 6). In the beginning of the day, the energy is low and significant fouling was observed due to blockage of the UF membrane by organic matter. To alleviate this problem, an air bubbler was required, which due to the high-energy requirement needed to be powered with a diesel generator. This measure was successful in maintaining UF flux and with this the supply of sufficient water to the pump and the NF module. Without bubbling this was not possible. As explained above, the feed concentration increases gradually over the day, while UF permeate, NF permeate and concentrate remain generally stable.

In the middle of the day, the air bubbler stopped temporarily (for diesel refill) and a visible decrease in feed concentration is observed due the deposition of organic matter on the membrane. The difference in TOC and dissolved organic carbon (DOC) (differentiated by the filtration of a 0.45-μm filter) indicated that the organic matter is predominantly dissolved. UF permeate and concentrate concentrations increase simultaneously, indicating that the deposition of organic matter leads to an increase of permeation, presumably through concentration polarization and subsequent diffusion of the smaller fractions. The NF permeate is unaffected until the very end of the day when the decreasing solar irradiation takes its toll and a gradual increase in TOC is observed. It should be noted here that the TOC analyser used cannot oxidise all of the low- molecular-weight organics that permeate the NF. This has resulted in liquid chromatography organic carbon detection (LC-OCD) detecting significantly higher TOC results,[28] which may also be the case here. Given the extreme TOC concentration, fractions of low-molecular-weight organics are important in concentration. This can result in a very high regrowth potential.[29]

The high organic matter content and surfactant characteristics of the tropical blackwater are evidenced in strong foam development caused by the air bubbling as shown in Fig. 7a. Fouling of the submerged UF is evidenced through a brown discolouration of the submerged UF membranes (Fig. 7b), while the drastic 'colour' removal can be seen in Fig. 7c, d with the very black feed waters, brown UF permeate and concentrate and perfectly clear NF permeate. The taste of this water was 'wholesome', very fresh and natural with no unpleasant taste. This was a great outcome, and quite the opposite to Mdori water that tasted, following treatment, like rotten eggs. This was due to the remaining hydrogen sulphide (H_2S) gas, probably originating from anaerobic microbiological activity in the groundwater, which required further treatment using chlorine bleach.

Community response to water produced

At both sites, the community was involved at varying extent in the field trials, in particular through school visits organised through teachers. At Mdori, significant preparative work was carried out through prior visits and discussion with various community stakeholders. Treatment of this water was most welcome due to a chronic water shortage in this dry region. The site was owned by the Anglican church (Kilimanjaro Diocese) and making this water drinkable would significantly reduce the water fetching distance, duties carried out predominantly by women and children. Due to the high fluoride concentration, the water was used for washing and animal feeding only. Producing water during the brief field trail and making this available to the community was greeted with great enthusiasm despite the foul smell of the water. Very rapidly a queue formed and the water was fetched. A technician of the local water committee volunteered to deal with the 'minor issue' of foul smell of the water and a trial using chlorine bleach was carried out to remove the H_2S, inevitably replacing this with some taste of chlorine. Due to the absence of organic matter (and hence colour) in this water, no visible improvement in water quality was achieved, and consumers simply trusted the technology. School children, teachers, community stakeholders, main users women and countless children, as well as the Bishop who travelled from Arusha to witness the trial showed overwhelming enthusiasm of being chosen to demonstrate such advanced technology, which admittedly looked like out of space with all the sensing equipment. A drawback of such research activity is the demonstration of a hope-inspiring solution is followed by the disappearance of the team, and the technology that promised the long awaited solution. A lack of interest by local government and aid organisations alike was noted, despite the evidenced financial viability of such technologies.

In Ngare Nanyuki, the community interaction preceding the actual work was significantly less due to uncertainty if such a field trial could indeed take place. Further, accessing the region was more complicated due to the need to circumvent the Arusha National Park. Interestingly, the enthusiasm of school children, including some selective scientific high schools, was immense. Community acceptance of this water, evidenced through willingness to collect and consume this water was absent, despite the exceptionally wholesome (good) taste of the water. Voicing this surprise to some of the teachers and community leaders, the answer was straight. This very black water was clearly bewitched and there was no way that any technology could possibly remove this 'characteristic'. As it turned out, the willingness to consume clear water with a very high fluoride content, was despite knowledge of the health implication far more appealing. The headmaster of the local school has built a water treatment system using ultraviolet (UV) technology (of uncoloured water) and constructed a miniature Mount Kilimanjaro to fulfil community expectation that pure water comes from the mountains. The most prominent local bottled water brand is indeed named Kilimanjaro. Such experiences highlight the importance of community engagement in finding solutions that take the reservations seriously. These observations are similar to the reservations to potable water reuse in some countries.[30] Much work is to be done to account for the cultural factors that contribute to long-term success of technologies.

DISCUSSION

Technically, the solar-powered UF-NF system performed brilliantly with somewhat extreme waters, which are not obvious drinking water sources. Resilience to fluctuating energy and a daily water production enables the provision of drinking water to some 200 people, assuming a daily consumption of 5 L. The concentrate could, in the case of Mdori, be used for washing and animal-feeding purposes and, in the case of Ngare Nanyuki, additionally for irrigation.

Energy fluctuation impacted on water quantity and quality. Water quantity reduced with declining solar irradiance and hence transmembrane pressure. This led to an increased solute concentration in the form of F, IC and salt (EC). The amount of water produced of higher concentration was low and, hence, the contribution of this to overall water quality was minor. TOC was vastly unaffected by fluctuation but increased at extreme concentrations. The SEC at 1–2 kWh/m^3 is very good, particularly given the small scale of the system. This is attributed to careful membrane selection with a focus of optimised permeability at adequate retention. Economic feasibility was discussed in detail elsewhere.[4] Community interactions have indicated both significant excitement of school pupils in the technology, as well as cultural acceptance issues in water technologies, not dissimilar to those encountered in water reuse. While the tropical 'blackwater' presented no doubt a scientific challenge, many less controversial water sources can be found before such 'bewitched' sources are required. However, the experience may indicate the need to think twice before proceeding with western water reuse approaches in rural Africa that may be considered entirely inappropriate.

Naturally, the results presented are short-term (1 day) research and general feasibility tests demonstrating that such treatment is technically feasible. Much is to be done from business models to legal frameworks, operation and maintenance, maintaining water quality after treatment, and building an infrastructure that can support such technologies in the long term, especially with technical skills. Significant further work is required in terms of technology adaptation, which involves (i) turning a mobile research unit with extensive sensing capability to a robust device that can withstand long-term operation; (ii) designing an operation and maintenance strategy that is suitable for remote areas and harsh conditions and (iii) designing a business and governance strategy that overcomes the nontechnical obstacles to provision of safe water.

Carrying out first-class research for 18 months in Tanzania has opened our eyes to the immense challenges of succeeding with this task. Corruption, theft and dishonesty—at all levels from kindergarten through to government—often experienced as artificial bureaucratic obstacles from customs to permissions are broadly discouraging. Taking part in corrupt practices is often perceived as the only option and will no doubt encourage more of it. Apathy is often present in society, compounded by the fact that the structure is lacking for people to pressure governments into action. Discrimination of both minorities and what is perceived as ex-colonialists will need to be translated into cooperation and open exchange of learning from each other in both directions. A history of exploitation and the perception that top-down aid is often an avenue to dispose of second-grade products when 'developed' markets are exhausted are contributing negatively. Deploying such state-of-the-art technologies generates a sense in receiving communities of feeling valued and provides the opportunity for a paradigm shift in the design of novel technologies in areas that are not yet constrained by aging infrastructres (such as distribution systems). Antiquated opinions that in Africa everything must be cheap must be replaced with an openness to deploy appropriate, yet advanced technologies that are capable of providing safe water quality in the long term. Naturally this requires development of maintenance infrastructure and remote sensing approaches able to monitor dissolved contaminants and system performance in general. Exploiting the opportunity of areas without water and power and water infrastructure provides an opportunity to implement state-of-the-art decentralised technologies that can make a huge difference. The access to water and energy may foster local opportunities and reduce the mobility towards cities or abroad in search for better livelihoods.

Most encouraging has been to observe and experience the incredible creativity and problem-solving skills, especially in rural areas. From making spare parts in makeshift workshops equipped with solid German mechanical tools with incredible skill taught at technical colleges through to fixing a car with nothing in the middle of nowhere indicates that everything is possible with an abundance of such great skill. Bridging such creativity and skill together with advanced technology to solve the global challenge of provision of clean water is no doubt the most rewarding engineering challenge of our time.

METHODS

Field test site selection and location

During 2012–2014, some 200 water samples were collected from sites in northern Tanzania to establish the range of common water quality parameters. The sampling sites were published previously.[14] From those

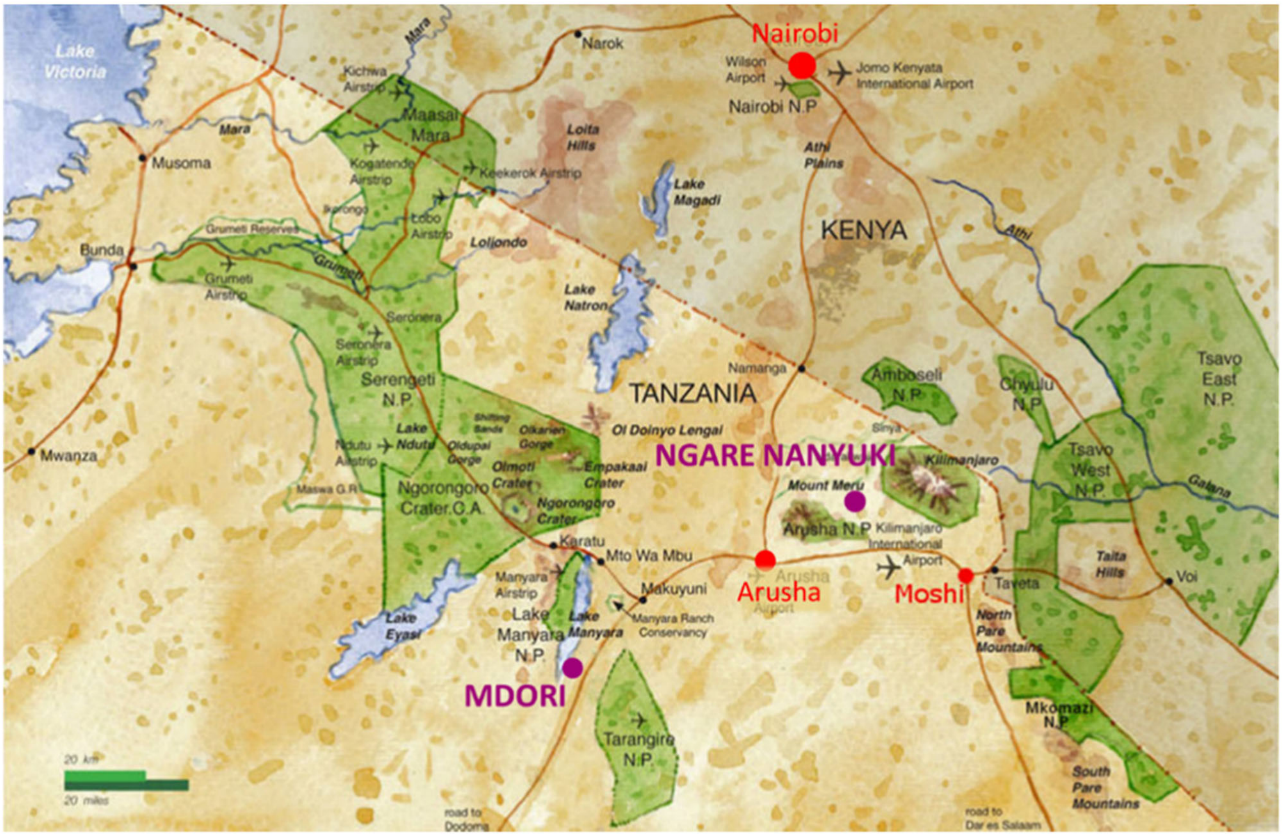

Fig. 8 Map of Northern Tanzania with sampling sites (green shading represents National Parks) with **a** Mdori test site in the Babati Rural District in Lake Manjara region (S03°47.273′, E035°51.138′) and **b** Ngare Nanjuki test site in the Arumeru District of the Arusha Region (S03°10.929′, E036°51.676′) (reproduced with permission by Africa Adventure Company, USA)

results, a number of sites were selected for further investigation and treatment of water at the Ngurdoto Defluoridation Research Station (NDRS). Two samples were subsequently chosen for field trials, Mdori (S03°47.273′, E035°51.138′) and Ngare Nanyuki (S03°10.929′, E036°51.676′). The location of these sites is shown in Fig. 8.

Field test site water quality: Mdori and Ngare Nanyuki

Both waters are high in fluoride, where the region has fluoride concentrations that are amongst the highest in the world. The water types are carbonaceous, while the organic matter stems from swamps in the foothills of Mount Meru (Ngare Nanyuki), an area that is well documented.[31] Mdori water has high fluoride and high inorganic content, while the organics concentration is low. Ngare Nanyuki water has high fluoride and high inorganic content, while the organics concentration is high. Calcium and turbidity of both waters are low (Table 1). The osmotic pressure of the Mdori water is in the range of 2.8–3.0 bar, the former determined from conductivity measurements and the latter via a full ion analysis. For the Ngare Nanyuki water, the osmotic pressure is in the range of 2.1–2.3 bar, via the same analysis.

Analytical methods

'Pure water' was used for all analytical procedures in the form of "Mt Meru" bottled water. This water is local surface water treated by RO, ozonation and UV irradiation and hence the highest quality water available (pH 7.2, EC ≤18 µS/cm, TOC <0.01 mg/L, fluoride <0.01 mg/L).

TOC and DOC of samples were analysed with a Sievers 900 TOC analyser (GE Analytical Instruments, Boulder, CO, USA) at the NDRS. Samples with expected TOC/DOC >10 mg/L were diluted with pure water.

$UV_{254\,nm}$ was analysed using UV-2800 Spectrophotometer (UNICO, Fairfield, NJ, USA) using quartz cuvettes with a path length of 1 cm and pure water reference at Nelson Mandela African Institute of Science and Technology (NMAIST). Specific UV absorbance, SUVA, was determined by the quotient of $UV_{254\,nm}$ and DOC. For UV and DOC analyses, the feed water samples were pre-filtered using a 0.45-µm Minisart syringe filter (cellulose acetate, Sartorius, Germany). Permeate samples were not filtered.

For pH and electric conductivity analyses, a multimeter (Multi 340i, WTW, Germany) was used with a pH electrode (SentTix 41) and a conductivity electrode, respectively (TetraCon 325). Turbidity of the feed waters was measured using a turbidimeter (TN-100, Eutech Instruments, USA).

Fluoride ion (F^-) concentration was determined by an ion-selective electrode in conjunction with an Ag/AgCl reference electrode with a pH meter (826 pH Mobile Meter, Metrohm, UK (NMAIST)). A total ionic strength adjustment buffer solution of pH 5–5.5 was used to reduce interferences resulting from pH and EC. Cations were measured using inductively coupled plasma optical emission spectroscopy (Vista-PRO CCD Simultaneous, Varian, The Netherlands), while anions were quantified anions using an ion chromatograph equipped with a suppressor detection unit (IC 790, Metrohm, Germany). Detailed methods were published previously.[32]

Renewable energy-powered membrane system set-up and operation

The solar-powered membrane system is depicted in Fig. 2 and a schematic in Fig. 9. The system was mounted on a trailer and described in detail previously.[27] Modifications were carried out in terms of the UF module that was since replaced with a custom-built Zenon Zeeweed (ZW230) module. A 4 in. NF90-4040 membrane module was used for all experiments reported in this paper. For the field trial, the pump is powered with two 150-W PV panels (BP Solar, BP3150S) directly. The PV panels are mounted onto a single-axis solar tracker (Mono-Pumps Australia) which is guided by a global positioning system. The solar irradiance is treated with a maximum power point tracker to optimise available power.

The fluctuations affect transmembrane pressure and flow, while the system is operated at a standard set point to ascertain reproducible operation. As opposed to experiments at the NDRS with this water,[28] the permeate is collected in a tank instead of being recirculated. For the Ngare Nanyuki water, an air bubbler (Medo LA-120, Nitto-Kohki, Japan) powered

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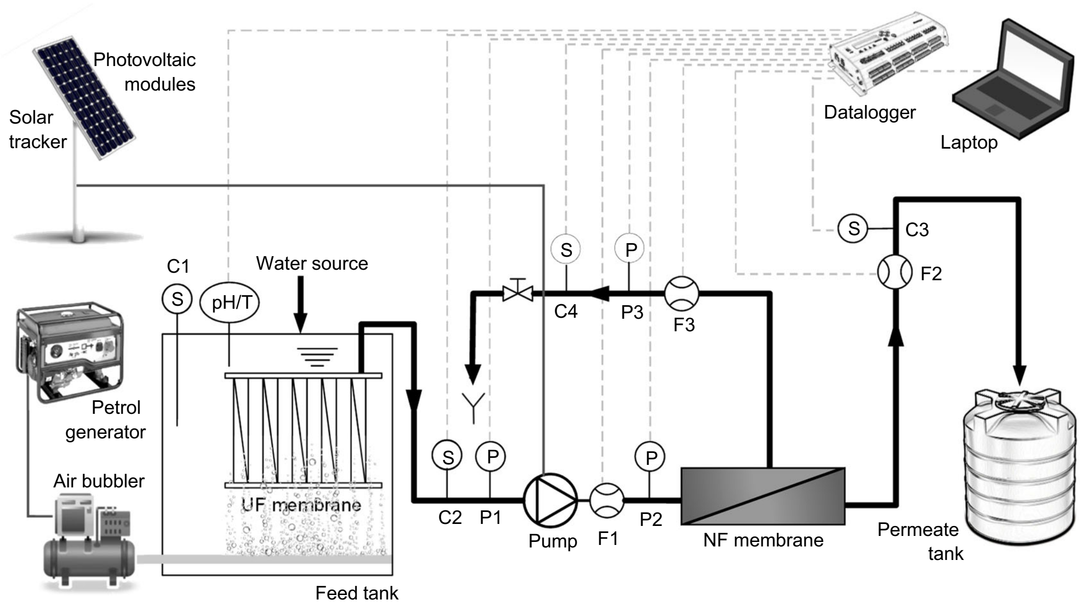

Fig. 9 Schematic of the renewable energy-powered membrane system (C1 feed sample, C2 UF permeate sample and sensor, C3 NF permeate sample and sensor, C4 concentrate sample and sensor, Fi flow metres, Pi pressure sensors)

Table 2. NF90 membrane characteristics (data adapted from refs [34,35])

Membrane	MWCO (Da)	Pore radius (nm)	NaCl retention (%)	Permeability[a] (L/h·m^2·bar)	Zeta potential[b] (mV)	Contact angle[c] (°)
NF90	100	0.34	83.7	9.7	−26	47.9 ± 1.7

MWCO molecular weight cut-off
0.1 M NaCl, at 10 bar
At pH 8, in 20 mM NaCl and 1 mM $NaHCO_3$
At pH 8, in 1 mM KCl

with a diesel generator (Honda Eu10i 1 kVA) was used. The feed tank is filled continuously with feed water, while the concentrate is discarded.

Membrane type and characteristics

The NF90 nanofiltration membrane from DOW Chemicals Company was selected for this study. Membrane characteristics are summarised in Table 2. The UF pre-treatment membrane was a Zenon ZW230 (GE Water, USA), which was used as a prototype based on the more common ZW500 module.[33] The polyvinylidene fluoride fibres exhibit a nominal pore size of 0.04 µm, an inner/outer diameter of 0.8/1.9 mm and the nominal surface area of the module is 21 m^2.

Calculation of filtration parameters

Permeate flux, J, was calculated using Eq. (1)

$$J = \frac{1}{A_M \rho_w} \frac{\Delta m_{\mathrm{Permeate}}}{\Delta t}, \qquad (1)$$

where A_M is the membrane surface area (m^2). Water density, ρ_w (kg/L), was determined with average feed water temperature during filtration.

TOC retention, R, was calculated using Eq. (2):

$$R = 1 - \frac{\mathrm{TOC}_{\mathrm{Permeate}}}{\mathrm{TOC}_{\mathrm{Feed}}}, \qquad (2)$$

where the TOC concentration (mgC/L) $\mathrm{TOC}_{\mathrm{Feed}}$ and $\mathrm{TOC}_{\mathrm{Permeate}}$ were measured before and after experiments. For calculation of recovery, R_W, Eq. (3) was used:

$$R_W = \frac{\sum^{V}_{\mathrm{Permeate}}}{V_{\mathrm{Feed}}}, \qquad (3)$$

where V is the volume of the respective samples (mL).

DATA AVAILABILITY

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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AUTHOR CONTRIBUTIONS

A.I.S. has planned the research and written the first draft of the manuscript. B.S.R. has contributed the renewable energy methods and analysed data. J.S. conducted experiments and the majority of sample analysis. All authors have contributed to manuscript revisions.

ADDITIONAL INFORMATION

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