CHEMICAL ENGINEERING TRANSACTIONS

VOL. 106, 2023

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Jeng Shiun Lim, Nor Alafiza Yunus, Peck Loo Kiew, Hon Huin Chin

**ISBN** 979-12-81206-05-2; **ISSN** 2283-9216

DOI: 10.3303/CET23106130

# Rainwater to Potable Water: Mini Review

How Chee Yang[a], Mazura Jusoh[a,b,*], Zaki Yamani Zakaria[a], Aishah Rosli[a]

[a]Faculty of Chemical and Energy Engineering, Universiti Teknologi Malaysia, 81300 Johor Bahru, Johor.
[b]Institute of Bioproduct Development (IBD), Universiti Teknologi Malaysia, 81300 Johor Bahru, Johor.
r-mazura@utm.my

Rainwater can serve as a safe and sustainable source of drinking water. From its formation and collection, rainwater can be contaminated by the surrounding atmosphere, dissolving various gases like carbon dioxide, sulphur oxides and nitrogen oxides to form various inorganic acids. These acids further promote contamination by dissolving metals and metal oxides that the rainwater encounters. On the other hand, depending on the cleanliness of the rainwater harvesting system, rainwater may be exposed to biological contaminants like pathogenic organisms from plant and animal origins and dust from dry deposition of particulate matter from the atmosphere. While all these contaminations can be dealt with relatively easily with modern water treatment technologies like media filtration, membrane technology and chlorination, rainwater is not as widely used as a source of drinking water as it should be, primarily due to a lack of incentives from the policy makers and availability of more accessible and abundant water sources like municipal water and groundwater. Above all, rainwater is not a reliable source of water as it is intermittent and can be unpredictable even with state-of-the-art weather forecasting. Thus, using rainwater as potable water source might only be suitable during rainy season and floods. The objective of this paper is to briefly review the technologies in purifying rainwater to potable water, and subsequently recommend an alternative technology called progressive freeze concentration (PFC) for the water purification purpose. Preliminary results with the new setup show that PFC can reduce the total dissolved solids (TDS) in rainwater by 83 - 96 % to produce ice that has less than 10 ppm TDS, with 75 – 90 % recovery. By comparing with reverse osmosis (RO), PFC has considerably lower capital and operating cost. Therefore, more research will be conducted to establish the feasibility of using PFC to purify rainwater and encourage the use of rainwater as a source of potable drinking water.

## 1. Introduction

Water is essential to life as we know it. For the sustenance of human lives, clean, liquid water is necessary, which unfortunately is not present in every part of the earth. Historically, human civilizations were built on places with natural access to clean water like rivers and lakes. As time went by, wells and artificial reservoirs were also constructed to improve water security. In the modern era, water treatment plants with water sources previously thought to be unfeasible like seawater and industrial effluent were also constructed due to increasingly scarce raw water sources. Despite all these efforts, one important water source remains overlooked, especially by affluent countries. Harvesting and using rainwater directly was not used in any significant way, despite the relatively high purity and ease of access compared to other water sources.

### 1.1 Rainwater and Its Issues

In the crudest form, rainwater can simply be harvested by having a basin outdoors while it is raining. The collected rainwater can be used for any purpose, including cleaning, irrigation and even as potable water if the basin is clean. One obvious problem with this is a supply-demand mismatch, which is also a common issue with renewable energies. This means that it does not always rain (supply) when water is needed (demand), if at all. The reliability of a raw water source often outweighs the quality of it. Other raw water sources like rivers, reservoir and underground water are often used in municipal water supply as the water treatment plants are designed with reliability in mind. Another reason that rainwater is not used is the concern on rainwater quality and contamination. This reason often limits the rainwater use to non-potable use only, due to safety reasons,

Paper Received: 14 July 2023; Revised: 05 August 2023; Accepted: 15 September 2023
Please cite this article as: Yang H.C., Jusoh M., Zakaria Z.Y., Rosli A., 2023, Rainwater to Potable Water: Mini Review, Chemical Engineering Transactions, 106, 775-780 DOI:10.3303/CET23106130

especially when tap water is readily available for human consumption. Some communities have been drinking rainwater with no increased risk of gastrointestinal disease reported (Chubaka et al., 2018).

### 1.2 Toxicology of Rainwater

From the toxicological point of view (Paracelsus' theory), no substance is absolutely safe (Gruiz et al., 2015), as everything influences human health, and given enough dose, adverse effect. In the context of drinking rainwater, one of the prevailing issues is waterborne disease. These diseases are caused by pathogenic organisms, including protozoa, bacteria and viruses present in contaminated water. When exposed to contaminated water, victims will develop severe diarrhoea and vomiting. If left untreated, dehydration and fatal hypovolemic shock follow. Any rainwater harvesting system meant for potable use should be able to disinfect the rainwater and if possible, prevent contamination in the first place by keeping the rainwater harvesting system clean and regularly maintained. Another issue is the presence of inorganic ions in the rainwater, which could have effects ranging from negative impacts to human health caused by heavy metal ions to unpalatable taste caused by hardness. Thus, for potable use, rainwater needs to be purified accordingly. This current work will briefly review the purification processes available, as well as a new technology called progressive freeze concentration (PFC).

### 1.3 Potential Use of Rainwater

Rainwater is free, in the sense that renewable energies are free. It can be collected on any building with a roof, with minimal piping modification to include a storage tank to partially address the reliability issue and adequate water treatment system to tackle the quality issue. If rainwater is not collected during the rain, it will inevitably flow into storm drains in urban areas, and if the storm is severe enough, flash floods will occur. By collecting and diverting the flow of rainwater away from storm drains, the risk and impact of flash floods are alleviated, reducing the chance of catastrophic loss of human lives and damage to properties. According to the Street, Drainage and Building Act 1974 in Malaysia, local authorities can mandate developers to construct buildings with provision to store rainwater during storm events with the primary intention of flood mitigation and prevention of water bodies pollution.

### 1.4 Rainwater Harvesting

Rainwater is most commonly collected by runoffs from roofs. Ideally, the roof surface area should be as large as possible, made from materials that do not leach harmful chemicals and away from any trees or obstructions. Horizontal gutters installed at the edge of the roofs collect and divert runoffs to vertical downpipes connected to rainwater storage tanks. Depending on intended use, rainwater can be used either directly from the storage tank or treated further for more critical use. According to a review by Alim et al. (2020), harvesting rainwater for potable use is not common in urban areas as centralized water supply is available. While the review is very comprehensive, it lacks explanation on how common contaminants found in rainwater affect human health. This paper will examine the relative risks of each contaminant and the necessity of removing them in order the maximise benefits against the risks and costs of drinking rainwater.

## 2. Drinking Water Quality Standards around the World

Each country has their own set of regulations governing the drinking water quality standard within their own jurisdiction. In the following section, the drinking water quality standards of several countries will be examined in detail with some background context. An important thing to note is that exceeding the limit of the standard does not necessarily mean the water is unsafe to drink. If exceeding the limit means the water is unsafe to drink, then every country would have the same limit, but it's not the case as shown in Table 1. Complying with the limit set by the government does mean that the water is wholesome, a legal term used to describe the compliance of water with local drinking water regulations.

*Table 1: Drinking water quality standards for WHO, Malaysia and the US*

| Parameters | WHO (World Health Organization, 2022) | Malaysia (Ministry of Health Malaysia, 2004) | US (United States, 2009) |
|---|---|---|---|
| pH | NA | 6.5 - 9.0 | 6.5 - 8.5 |
| TDS (mg/L) | NA | 1,000 | 500 |
| Nitrate as N (mg/L) | 11.3 | 10 | 10 |
| Colour (TCU) | NA | 15 | 15 |
| Turbidity (NTU) | NA | 5 | 5 |
| E. Coli | Absent | Absent | Absent |

### 2.1 World Health Organization (WHO)

The World Health Organization (WHO) has published Guidelines for Drinking Water: Fourth Edition Incorporating the First and Second Addenda in 2022 with the primary objective of providing a basis for legislators around the world to enact sound and informed policies regarding water and public health. Contrary to other national drinking water quality standards, WHO does not impose a limit on various common parameters like pH, TDS, colour and turbidity, as there is insufficient evidence to suggest a negative impact on human health from exposure to those parameters, even at relatively high concentration.

### 2.2 Malaysia

There is no legislation on the quality of drinking water from the public water supply systems in Malaysia (Malay Mail, 2022). The Ministry of Health Malaysia (2004) has published the National Standard for Drinking Water Quality and monitors the quality of water supply with water purveyors. The Food Act 1983 and Food Regulations 1985 regulate the quality of natural mineral water, packaged drinking water and vended water.

### 2.3 United States

In the United States, the Environmental Protection Agency (EPA), empowered by the Safe Drinking Water Act, is responsible for setting standards and regulations for public drinking water systems (United States, 1974). In National Primary Drinking Water Regulations (NPDWR), legally enforceable standards called maximum contaminant levels (MCL) are established to protect the public against contaminants that pose a risk to human health (United States, 2009). EPA has also established National Secondary Drinking Water Regulations (NSDWR) that set non-mandatory secondary maximum contaminant levels (SMCL) to serve as guidelines for the public. Examples of contaminants in NPDWR and NSDWR are shown in Table 2.

*Table 2: Examples of contaminants in NPDWR and NSDWR*

| NPDWR | NSDWR |
|---|---|
| Nitrate and Nitrite | pH |
| Turbidity | Total Dissolved Solids (TDS) |
| E. Coli | Colour and Odour |
| Copper | Chloride |
| Heterotrophic Plate Count (HPC) | Sulphate |

## 3. Rainwater Quality

There are many parameters which can be measured in any water sample, provided unlimited time and budget. Water professionals often must decide which parameters to quantify and report, given the source of water, availability of analytical equipment and use of the treated water. As this paper describes the process of treating rainwater to potable water, the parameters discussed further are based on contaminants commonly found in rainwater that are direct or indirect indicators of risk to human health and are relatively easy to measure in-situ. The list is non-exhaustive and can be modified according to the specific needs and environment of the study.

### 3.1 pH

According to WHO (2022), pH per se has no direct impact on consumer health. There is no guideline on pH by WHO. Similarly, the US has a non-enforceable guideline on pH. It is almost always measured in water treatment plants as an important operational quality. Extreme pH value can cause corrosion of the surface in contact with the water and ineffective chlorine disinfection. Natural, uncontaminated rainwater is slightly acidic at pH 5.64 (Girard, 2013) due to the dissolution of carbon dioxide naturally present in the atmosphere and formation of weak carbonic acid in rainwater. This is already below the lower limit of pH 6.5 in Malaysia drinking water quality standard. Compounded by the effect of acid rain formation due to anthropogenic release of sulphur oxides and nitrogen oxides into the atmosphere, pH of rainwater as low as 3.67 (Abdullah et al., 2022) has been recorded. No rainwater was found to exceed the higher limit of pH 9.0 according to existing literature.

### 3.2 Total Dissolved Solids (TDS)

Like pH, the presence of naturally occurring TDS poses no health risk to consumers (WHO, 2022). When the level of TDS becomes higher, the water will be less palatable for drinking and lead to excessive scaling on the surface in contact with the water. TDS is also an indicator of the degree of contamination relative to pure water. Rainwater with TDS as low as 0 ppm was found in an unpolluted environment (Sumari et al., 2010), which is on par with lab grade deionised water. In urban areas, the TDS of rainwater is usually less than 100 ppm (Lee et al., 2010) with one study having a sample with 127 ppm TDS (Xu and Han, 2009).

### 3.3 Nitrate

Nitrate at elevated levels in water can pose a health risk as it can cause methaemoglobinaemia or blue-baby syndrome in infants. Nitrate can be reduced to nitrite in the gastrointestinal tract, which then binds with haemoglobin in red blood cells to form methaemoglobin, which prevents effective oxygen transport in the body. High levels of methaemoglobin formation can give rise to cyanosis, commonly referred to as blue-baby syndrome (World Health Organization, 2022). The WHO has set a limit of 50 mg/L for nitrate in water or 10 mg/L for nitrate measured as nitrogen by the US and Malaysia. Except for one study (Abdullah et al., 2022), no rainwater sample was ever found to exceed the limit of 10 mg/L in existing literature.

### 3.4 Colour and Turbidity

Drinking water should not have any visible colour and turbidity present, regardless of whether health risks exist. This is because no amount of data and reports can convince anyone to drink a cup of turbid, coloured “drinking water”. In rainwater, the source of colour and turbidity usually stems from particulate matters in the atmosphere and contamination of the rainwater harvesting system from plant and animal origin. During chlorine disinfection, if the source of colour is due to dissolved organic matter, this group of compounds can form disinfection byproducts, which are possibly carcinogenic. Likewise, the turbidity causing suspended solids can render ultraviolet (UV) sterilisation ineffective by shielding pathogens from the sterilising UV radiation. Fortunately, humans can detect colour and turbidity as low as 15 TCU and 4 NTU (World Health Organization, 2022).

### 3.5 E. Coli

Escherichia Coli (E. Coli) is a gram-negative, facultative anaerobic, rod-shaped, coliform bacterium commonly found in the gastrointestinal tract of warm-blooded organisms (Rice et al., 2012). Although not pathogenic itself, its presence in water often implies the presence of faecal material in water and other pathogenic organisms. It has been widely used as an indicator organism to quantify the degree of biological contamination in the water. Water intended for human consumption should contain no faecal indicator organisms. Some studies suggest that the presence of E. Coli in water has no direct relationship with waterborne disease outbreaks (World Health Organization, 2022). Though E. Coli has been found in rainwater (Chubaka et al., 2018), it can be easily neutralised by boiling the water, UV sterilisation or chlorination.

## 4. Rainwater Treatment

Despite all the contaminants discussed in the previous section, rainwater can be treated with relative ease to drinking water quality, with some or all the techniques in the next section, depending on the raw rainwater quality. Three common techniques used in rainwater filtration systems, media filtration, membrane technology and chlorination, are chosen due to their established performance data, easily procured and relative ease of use by laypersons. Notwithstanding that, a novel technique, cold solutes separation that is never used before in rainwater treatment will also be discussed to introduce readers to this promising technique.

### 4.1 Media Filtration

In its simplest form, filtration can be a cloth used to strain a cup of coffee from its ground. Filtration is usually done to either remove impurities or to recover valuable substance from a solution (Purchas, 1996). Depending on the purpose of the filtration system, different types, particle size and arrangement of media can be used to maximise the performance of the filter in terms of removal efficiency and pressure drop across the filter. Virtually any material that is permeable like natural and synthetic fibres or can be made permeable like metal and glass, can be good filter media. This makes media filtration one of the most versatile and ubiquitous filters used in the world, from household point of use drinking water filters to industrial wastewater treatment plants. The working mechanisms in filtration are surface straining, depth straining, depth filtration and cake filtration. Most filters work by a combination of mechanisms. Performance of the media filter can be altered by surface coating, e.g., Ahammed and Meera (2010) showed that a dual-media filter consisting of manganese oxide- and iron hydroxide-coated sand can achieve 99% removal of total coliforms from rainwater. Media filtration should be coupled with further disinfection to ensure safe drinking water free from pathogenic organisms.

### 4.2 Membrane Technology

Like media filtration, membranes are also used to remove particulate matter from water. In almost all membrane filtration setup, feed raw water does not completely pass through the membrane Permeate is the portion that passes through the membrane while retentate or concentrate is the portion that does not pass through the membrane. While many types of membrane exist to serve a multitude of different purposes, two main types of membrane, ultrafiltration (UF) and reverse osmosis (RO) are the most widely used. UF can be used for rainwater with high amounts of suspended solids while RO can be used for rainwater with high levels of dissolved solutes (Liu et al., 2021). Common drawbacks of membrane technology include high investment cost, membrane fouling, and shorter lifespan compared to media filtration.

### 4.3 Chlorination

The oldest form of water disinfection is probably by boiling the water. Powerful oxidizing chemicals like chlorine and ozone are also highly effective to disinfect water with the main advantage of lower energy usage. Among the different chlorine species, hypochlorous acid, HOCl is the one having the highest disinfection kinetics and is highly effective against bacteria and viruses in the water (Howe et al., 2012). Protozoan pathogens can be highly resistant towards chlorination as they can form protective cysts, oocysts or eggs (World Health Organization, 2022). Fortunately, the size of protozoa is much larger than bacteria and can be removed easily by membrane or media filters. One emerging concern with using chlorination is the formation of disinfectant by-products (DBP) in chlorinated water as free chlorine will react with dissolved organic matter in raw water to form chlorinated or brominated compounds, some of which are suspected carcinogens. This risk can be mitigated by using combined chlorine or UV sterilisation. As rainwater contains precursor to DBP formation (Latif et al., 2023), DBP can form in rainwater when chlorinated. Hou et al. (2018) detected presence of DBP in chlorinated rainwater. Table 3 shows the characteristics of various commonly used disinfectants.

*Table 3: Characteristics of five most common disinfectants (Howe et al., 2012)*

| Effectiveness against | Free chlorine | Combined chlorine | Chlorine dioxide | Ozone | UV light |
|---|---|---|---|---|---|
| Bacteria | Excellent | Good | Excellent | Excellent | Good |
| Viruses | Excellent | Fair | Excellent | Excellent | Fair |
| Protozoa | Fair to poor | Poor | Good | Good | Excellent |
| Endospores | Good to poor | Poor | Fair | Excellent | Fair |

### 4.4 Alternative Technology: Progressive Freeze Concentration (PFC)

While all of techniques discussed are effective to remove certain contaminants, each of them has their own drawbacks and costs that prevents widespread use in treating rainwater to potable water. This paper will introduce a new technology for rainwater purification called progressive freeze concentration (PFC). In PFC, when an aqueous solution freezes, water molecules will preferentially crystallise on the nucleation site. Due to molecular size difference, contaminants will be rejected from the ice crystal lattice and remain in the mother liquor. By separating the ice crystals from the mother liquor pure water can be obtained, and rainwater with less water composition and reduced volume will be left behind, making this process suitable for concentration and purification purposes. Depending on the FC system setup and degree of supercooling, ice crystals may be formed in suspension (Suspension Freeze Concentration, SFC) or on the cooling surface (Progressive Freeze Concentration, PFC). While PFC produces large crystals that are easy to separate, its productivity is usually lower than SFC (Jusoh et al., 2008). The main advantage of FC systems is that it requires only 420 kJ of energy to produce 1 kg fresh water, which is six times lower than the energy required in distillation systems (Attia, 2010). PFC is widely used in the food industry to concentrate fruit juices and alcoholic beverages, but rarely in water treatment (Miyawaki and Inakuma, 2021). PFC has also been used to purify lake water with by reducing turbidity up to 99.6 % (Yahya et al., 2017). Preliminary results with a new setup show that PFC can reduce the TDS in rainwater by 83 - 96 % to produce ice that has less than 10 ppm TDS, with 75 – 90 % recovery.

## 5. Conclusions

Despite the challenges associated with using rainwater as potable water, rainwater has always been a vital source of water used for all purposes including irrigation, cleaning and drinking. It is not only renewable and relatively low cost to obtain and treat, but it is also one of the critical solutions towards ensuring water security to everyone, especially the populations vulnerable to water scarcity caused by pollution and climate change. As PFC is showing promising results of 83 - 96 % removal efficiency in TDS, PFC can, together with other technologies, novel and conventional, lower the economic and technical barriers in the proliferation of rainwater usage. More research should be done to encourage the use of rainwater as a source of potable water.

### Acknowledgments

The authors would like to acknowledge the financial support from the Ministry of Higher Education (MOHE) Malaysia under Fundamental Research Grant Scheme (FRGS) (FRGS/1/2022/TK05/UTM/02/17).

## References

Abdullah S.N.F., Ismail A., Juahir H., Ahmad R.B., Lananan F., Hashim N.M., Ariffin N., Zali M.A., Mohd T.A.T., Hussin M.H.F., Mahmood R.I.S.R., 2022, Chemical composition of rainwater harvested in East Malaysia, Environmental Engineering Research, 27(2), 200508.

Ahammed M.M., Meera V., 2010, Metal oxide/hydroxide-coated dual-media filter for simultaneous removal of bacteria and heavy metals from natural waters, Journal of hazardous materials, 181(1-3), 788-793.

Alim M.A., Rahman A., Tao Z., Samali B., Khan M.M., Shirin S., 2020, Suitability of roof harvested rainwater for potential potable water production: A scoping review, Journal of cleaner production, 248, 119226.

Attia A.A., 2010, New proposed system for freeze water desalination using auto reversed R-22 vapor compression heat pump, Desalination, 254(1-3), 179-184.

Chubaka C.E., Whiley H., Edwards J.W., Ross K.E., 2018, A review of roof harvested rainwater in Australia, Journal of environmental and public health, 2018, 6471324.

Girard J., 2013, Principles of environmental chemistry, Jones & Bartlett Learning, Burlington, United States.

Gruiz K., Meggyes T., Fenyvesi É. (Eds.), 2015, Engineering Tools for Environmental Risk Management: 2. Environmental Toxicology, CRC Press, Leiden, Netherlands.

Hou M., Chu W., Wang F., Deng Y., Gao N., Zhang D., 2018, The contribution of atmospheric particulate matter to the formation of CX3R-type disinfection by-products in rainwater during chlorination Water research, 145, 531-540.

Howe K.J., Hand D.W., Crittenden J.C., Trussell R.R., Tchobanoglous G., 2012, Principles of water treatment, John Wiley & Sons, Hoboken, United States.

Jusoh M., Yunus R.M., Hassan M.A., 2008, Effect of flowrate and coolant temperature on the efficiency of progressive freeze concentration on simulated wastewater, World Academy of Science, Engineering and Technology, 2(11), 308-311.

Latif S., Alim M.A., Rahman A., Haque M.M., 2023, A Review on Chlorination of Harvested Rainwater, Water, 15(15), 2816.

Lee J.Y., Yang J.S., Han M., Choi J., 2010, Comparison of the microbiological and chemical characterization of harvested rainwater and reservoir water as alternative water resources, Science of the Total Environment, 408(4), 896-905.

Liu X., Ren Z., Ngo H.H., He X., Desmond P., Ding A., 2021, Membrane technology for rainwater treatment and reuse: A mini review, Water Cycle, 2, 51-63.

Malay Mail, 2022, Khairy: Health Ministry to introduce Drinking Water Quality Act, Malay Mail <www.malaymail.com/news/malaysia/2022/04/07/khairy-health-ministry-to-introduce-drinking-water-quality-act/2052153> accessed 06.07.2023.

Malaysia, 1974, Street, Drainage and Building Act 1974, Act 133, Kuala Lumpur, Malaysia.

Malaysia, 1983, Food Act 1983, Act 281, Kuala Lumpur, Malaysia.

Malaysia, 1985, Food Regulations 1985, P.U.(A) 437/85, Kuala Lumpur, Malaysia.

Ministry of Health Malaysia, 2004, National Standard For Drinking Water Quality, Ministry of Health Malaysia, Putrajaya, Malaysia.

Miyawaki O., Inakuma T., 2021, Development of progressive freeze concentration and its application: A review, Food and Bioprocess Technology, 14, 39-51.

Purchas D. (Ed.), 1996, Handbook of Filter Media, Elsevier Advanced Technology, Oxford, United Kingdom.

Rice E.W., Bridgewater L., American Public Health Association (Eds.), 2012, Standard methods for the examination of water and wastewater (Vol. 10), American Public Health Association, Washington, D.C., United States.

Sumari S.M., Muhamad-Darus F., Kantasamy N., 2010, Rainwater characterization at Global Atmospheric Watch in Danum Valley, Sabah. In 2010 International Conference on Science and Social Research (CSSR 2010), 479-484.

United States, 1974, The Safe Drinking Water Act, Pub. L. 93-523, Washington, D.C., United States.

United States, 2009, National Primary Drinking Water Regulations, EPA 816-F-09-004, Washington, D.C., United States.

World Health Organization, 2022, Guidelines for drinking-water quality: incorporating the first and second addenda, World Health Organization, Geneva, Switzerland.

Xu Z., Han G., 2009, Chemical and strontium isotope characterization of rainwater in Beijing, China, Atmospheric Environment, 43(12), 1954-1961.

Yahya N., Lee W.J., Zakaria Z.Y., Ngadi N., Mohamad Z., Rahman R.A., Jusoh M., 2017, Water purification of lake water using progressive freeze concentration method, Chemical Engineering Transactions, 56, 43-48.