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Using soil and other accessible resources for the remineralization of water from sorbent-based atmospheric harvesting systems

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Mémoire présenté en vue de l'obtention du diplôme de *Maîtrise ès sciences appliquées*

Génie chimique

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Ce mémoire intitulé:

Using soil and other accessible resources for the remineralization of water from sorbent-based atmospheric harvesting systems

présenté par **Andres Felipe SANCHEZ RENDON**

en vue de l’obtention du diplôme de *Maîtrise ès sciences appliquées*

a été dûment accepté par le jury d’examen constitué de :

Mario JOLICOEUR, président

Jason Robert TAVARES, membre et directeur de recherche

Émilie BÉDARD, membre et codirectrice de recherche

Sarah DORNER, membre

DEDICATION

Aux expériences inattendues, pour les ouvertures et la métamorphose qu'elles amènent.

To the intangible learning wisdom of the adventurous life paths.

A los colegas, profesores, amigos, familia que he tenido y que he hallado a lo largo del camino.

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I am deeply grateful to all the people who have encouraged me to push my limits a little further every time, who have made me feel that I am enough without minimising the value of my efforts, and whose feedback has shaped me into a different person from the one I was when I started this program.

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I am also grateful to Polytechnique Montréal, the OPSIDIAN program, and all the students and professors I had the chance to learn from during my master’s. The Graduate Student Association, the conferences, and competitions, all of them played a role in my growth; they provided me with an incredible academic experience, helping me evolve and shape a better version of myself.

This journey would not have been possible without the financial support of OPSIDIAN, Prima, and NSERC, in collaboration with Awn Nanotech Inc. Thank you for funding this research project.

Thanks to the members of the jury for taking the time to evaluate my research project as part of my master's degree completion.

And last but not least, I would like to express my deepest gratitude to my supervisors for this project, for giving me the opportunity to work on this research with such a profound social impact, as is ensuring the right to water access and quality. Thanks to my professor, Jason Robert Tavares, for reminding me that making mistakes means that I am working, and for helping me to embrace the errors as valuable learning experience. Thanks to my professor, Emilie Bédard, for being a strong source of motivation when the expected results failed to appear. To both of you, thank you for your guidance, kindness, and trust; I am honored to have worked under your supervision.

RÉSUMÉ

La pénurie d'eau est un problème mondial croissant, intensifié par le changement climatique et les inégalités persistantes dans l'accès à la qualité de l'eau potable. La collecte atmosphérique de l'eau (AWH) est apparue comme une alternative prometteuse, en particulier dans les régions confrontées à des pénuries d'eau. Parmi les méthodes de collecte, les éponges nanoporeuses (NPS), qui sont des matériaux à base de carbone dérivés de précurseurs peu coûteux, se révèlent très efficaces pour capturer l'eau de l'AWH. Cependant, l'eau obtenue grâce aux technologies AWH basées sur les sorbants manque souvent de minéraux essentiels. Selon les directives de l'Organisation mondiale de la santé (OMS), les minéraux tels que le calcium et le magnésium sont essentiels non seulement pour la santé humaine, mais aussi pour améliorer le goût de l'eau.

Bien qu'il existe des méthodes de minéralisation conventionnelles comme Calcite, Corosex™ ou même des filtres minéralisateurs disponibles sur le marché, ce projet propose une stratégie de minéralisation à faible consommation qui exploite des matériaux naturels tels que les sols, les graviers et les sables locaux, afin d'améliorer la teneur en minéraux de l'eau collectée de l'atmosphère. Parmi les matériaux testés, la Terre noire de Charbonneau Floral (dosage de 0,03 g/mL) le et sable de plage rouge de l'Île-du-Prince-Édouard (0,25 g/mL) ont montré un fort potentiel d'amélioration de la dureté, atteignant des concentrations de 182 mg/L et 265 mg/L de CaCO3, respectivement. Une cinétique de libération rapide des ions a été observée, la saturation étant atteinte en 15 minutes.

Dans l'ensemble, cette approche contribue au développement de systèmes décentralisés, à faible consommation, pour fournir une eau non seulement accessible mais aussi de qualité et minérale, soulignant la valeur de l'utilisation de matériaux facilement disponibles pour répondre aux besoins humains fondamentaux et renforçant la faisabilité des technologies AWH en tant que solution prometteuse dans les communautés souffrant d'un stress hydrique.

ABSTRACT

Water scarcity is an escalating global issue, intensified by climate change and persistent inequalities in access to quality in drinking water. Atmospheric water harvesting (AWH) has emerged as a promising alternative, especially in regions experiencing water shortages. Among the collection methods, nanoporous sponges (NPS) which are carbon-based materials derived from low-cost precursors, show high efficiency in capturing AWH water. However, water obtained through sorbent-based AWH technologies often lacks essential minerals. According to World Health Organization (WHO) guidelines, minerals like calcium and magnesium are crucial not only for human health but also for improving taste.

Although there are conventional mineralization methods such as Calcite, CorosexTM or even mineralizing filters available on the market. This project proposes a low-consumable mineralization strategy that leverages natural material such as local soils, rock, and sands, to enhance the mineral content of AWH water. Of the materials tested, Black Earth soil from Charbonneau Floral (0.03 g/mL) and Red beach sand from Prince Edward Island (0.25 g/mL) showed strong potential for improving hardness, reaching concentrations of 182 mg/L and 265 mg/L $CaCO_3$, respectively. Fast ion release kinetics were observed, with saturation reached within 15 minutes.

Overall, this approach contributes to the development of decentralized, low-consumable systems for delivering not only accessible but also quality and mineral, highlighting the value of using readily available materials to address basic human needs and reinforces the feasibility of AWH technologies as a promising solution in water-stressed communities.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LISTE OF SYMBOLS AND ABBREVIATIONS

AWH: Atmospheric Water Harvesting

B: Boron

$Ca(OH)_2$: Calcium hydroxide / Hydrated lime

Ca^{2+}: Calcium

$CaCl_2$: Calcium chloride

$CaCO_3$: Calcium Carbonate / Calcite

$CaMg(CO_3)_2$: Dolomite

CaO: Calcium oxide

$CaSO_4$: Calcium sulfate

CCPP: Calcium Carbonate Precipitation Potential

CEC: Cation exchange capacity

Cl: Chlorine

Cl^-: Chloride

CO_2: Carbon Dioxide

CO_3^{2-}: Carbonate ion

Cr: Chromium

Cu: Copper

DOC: Dissolved Organic Carbon

ΔE: Cell potential under non-standard conditions

ΔE°: Standard cell potential and conditions (298K, 1 atm, 1 M)

EBT: Eriochrome Black T

$E^\circ_{H^+}$: Standard hydrogen electrode potential.

E_H^+: Hydrogen electrode potential under non-standard conditions

Fe: Iron

Fe_3O_4: Magnetite

$FeCO_3$: Siderite

F: Fluorine

$\gamma - FeOOH$: Lepidocrocite

$\alpha - FeOOH$: Goethite

$\beta - FeOOH$: Akageneite

H_2: Hydrogen

H_2CO_3: Carbonic acid

H_2O: Water

H_2SO_4: Sulfuric acid

HCO_3^-: Bicarbonate ion

I: Iodine

ICP-MS: Inductively Coupled Plasma Mass Spectrometry

IUPAC: International Union of Pure and Applied Chemistry

K: Potassium

KCl: Potassium chloride

Ksp: Solubility product constant

$Mg(OH)_2$: Magnesium hydroxide

Mg^{2+} : Magnesium

$MgCO_3$: Magnesite

MgO: Magnesium Oxide / Corosex™

Mn: Manganese

Mo: Molybdenum

Na^+: Sodium

Na_2CO_3: Sodium carbonate

$NaHCO_3$: Sodium bicarbonate

NaOH: Sodium hydroxide

n_e : Number of moles of electrons transferred in the redox reaction

NTU: Nephelometric Turbidity Units

P: Phosphorus

POU: Point of Use

Q: Reaction quotient

RPM: Revolutions Per Minute

Se: Selenium

$SO_4{}^{2-}$: Sulfate

Sr: Strontium

TDS: Total Dissolved Solids

THMs: Trihalomethanes

UN: United Nations

US: United States

UV: Ultraviolet

V: Volts

WHO: World Health Organization

Zn: Zinc

LIST OF APPENDICES

CHAPTER 1 INTRODUCTION

1.1 Context

For one month every year, at least 4 billion people face water shortages (**Figure 1.1**), increasing the perception of a global systemic risk [1]. Key strategies to mitigate this threat are becoming increasingly evident, including limits on water consumption per river basin, improved water use efficiency, and better allocation of limited resources to safeguard biodiversity and human welfare [2].

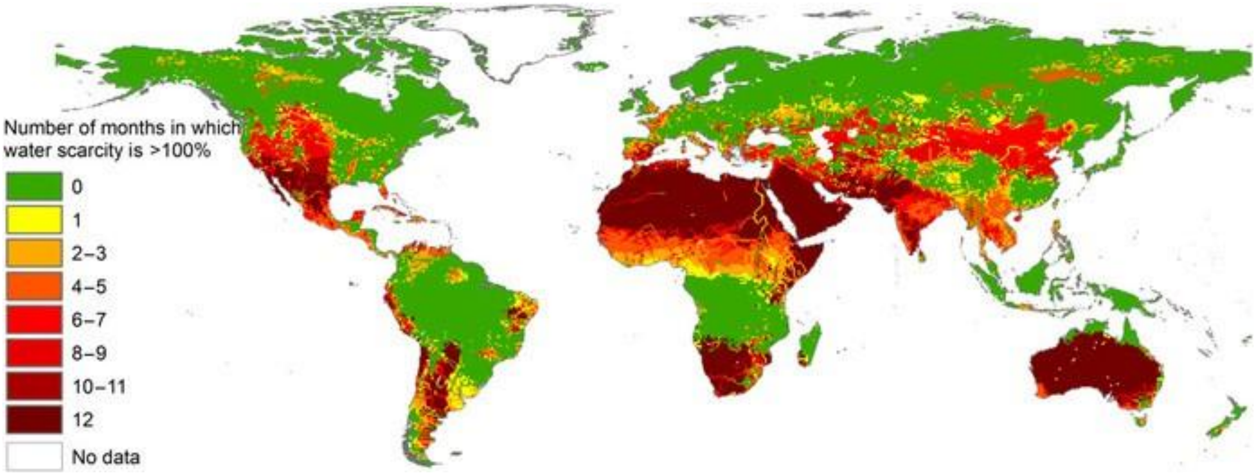

Figure 1.1. Global Water Scarcity. Reproduced from Mekonnen & Hoekstra, 2016 [3][a]

Water stress knows no boundaries and is getting worse due to climate change [4]. Cape Town, South Africa, had to impose severe restrictions on water consumption in 2018 due to extreme shortages, including higher water tariffs and reduced water pressure [5]. In 2021, Quebec faced a drought that highlighted the vulnerability of water resources even in water-abundant regions [6]. Concurrently, First Nations communities in Canada have been challenged by access to drinking water for several years [7,8], and the latest water crisis in Catalonia [9] shows how governments today are challenged to deal with water scarcity.

Access to quality water is fundamental right and essential to daily life. To address this need, various actions have been proposed, including governance and education. The UN Sustainable

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[a] Reproduced from: M. M. Mekonnen and A. Y. Hoekstra, "Four billion people facing severe water scarcity," *Science Advances*, vol. 2, no. 2, p. e1500323, Feb. 2016. DOI: 10.1126/sciadv.1500323. ©The Authors, some rights reserved; exclusive licensee AAAS. Distributed under a Creative Commons Attribution NonCommercial License 4.0 (CC BY-NC) http://creativecommons.org/licenses/by-nc/4.0/

Development Goals emphasize universal access to water and sanitation, highlighting the role of local communities in their management [10]. Similarly, the World Health Organization (WHO) underscores that safe drinking water is crucial for health and development at all levels. Moreover, investments in water and sanitation yield economic benefits by reducing health risks and medical costs. [11].

The atmosphere holds a substantial amount of freshwater, estimated at 13,000 km³ of water vapour. This volume is expected to increase with global warming [12]. Nonconventional water sources like Atmospheric Water Harvesting (AWH) show promise in accelerating decentralized access to water (**Figure 1.2**), as they could namely help secure water resources for underserved communities [13]. However, realizing this promise requires the development of cost-effective, off-grid devices that can be scaled efficiently.

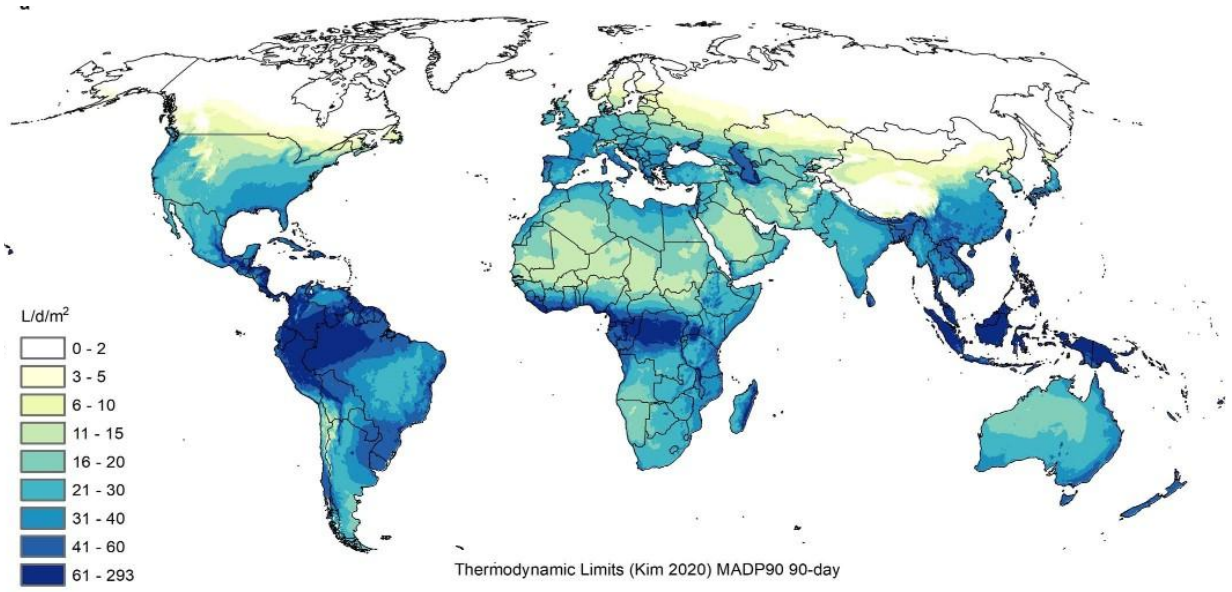

Figure 1.2. Atmospheric Water Availability. Reproduced from Lord et al., 2021 [12][b]

AWH has been developed in recent years through various approaches: some systems capture water by leveraging high ambient humidity, while others condense water from air using thermodynamic

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[b] Reproduced From: Lord, J., Thomas, A., Treat, N. *et al.* Global potential for harvesting drinking water from air using solar energy. *Nature* 598, 611–617 (2021). https://doi.org/10.1038/s41586-021-03900-w.©The Authors, some rights reserved; exclusive licensee Springer Nature. Distributed under a Creative Commons Attribution NonCommercial License 4.0 (CC BY-NC) http://creativecommons.org/licenses/by-nc/4.0/

cycles. Sorbent-based technologies, including gels, deliquescent salts, and nanoporous materials, reduce energy consumption by capturing water below the dew point. Among these, carbon-based adsorbents synthesized via pyrolysis of low-cost precursors offer high-performance , affordability, scalability and resilience [14,15]. Nanoporous materials capture water vapour through capillary condensation, adsorbing and subsequently releasing it in fast, repeatable cycles [16]. Optimization of these materials involves identifying the optimal configuration to maximize water uptake and improve daily water yield performance. The sorption capabilities of the material are further assessed through various experiments, comparing the performance across different conditions

1.2 Problem

AWH presents a viable alternative for remote communities that lack access to municipal water supplies. However, AWH technologies have prioritized water access before addressing water quality challenges. Examination of the quality of water produced by different AWH methods have focused on preventing contamination from materials such as iron (pipes and hoses), copper (foam, chambers, and solder alloys), silver, indium (solder alloys), and zirconium, lithium (deliquescent material compounds) [17,18]; comprehensive research on overall water quality remains limited. Understanding water quality variations in different water sources and their impact on public health is crucial, emphasizing the need to ensure AWH water safety for point-of-use consumption and bridge the knowledge gap. [19].

Water quality is defined by various parameters set by environmental organizations or governments through water treatment guidelines, such as those from Health Canada, the Environmental Protection Agency (EPA), and the WHO. Typically, Water quality assessments cover a wide range of factors, from microbiological to aesthetic parameters, including the presence of pathogens, pH, turbidity, organic chemicals, hardness, and metal concentrations[20]. However, there is no global consensus on certain parameters, such as minimum levels of essential ions in water, as these depend on the specific physicochemical conditions of each local source. The WHO, recognizing their relevance to health and water quality, has developed guidelines to address this variability.

According to the WHO, mineral content is another key parameter due to its impact the taste and health benefits of water [21]. Achieving a balance of essential minerals like calcium and magnesium is crucial, while harmful metals must be avoided.

Some commercial atmospheric water harvesting (AWH) devices include a mineralization stage as part of their features [22], employing mineral blocks to add essential elements such as sodium (Na^+), magnesium (Mg^{2+}) and calcium (Ca^{2+}), because AWH water tends to be low in these elements [23]. In fact, its composition is closer to deionized water than tap water.

The determination of a minimum mineral content in drinking water is an important consideration, given its influence on health and taste. The European Directive suggests an optimal remineralization range of magnesium between 20 to 40 mg/L and calcium between 40 to 80 mg/L [24]. However, the relevance of these thresholds depends on the specific context, particularly in communities with limited resources. The WHO states that drinking water can contribute approximately 5–20% of a person's daily mineral intake, with the remainder obtained from food [21].

There is limited research on water quality in AWH systems, both before and after treatment with no explicit focus on the methods or processes used for mineralization. Therefore, developing clear remineralization guidelines is essential to ensure the suitability of AWH water for various applications, including human consumption [25].

To improve the quality of the collected water, it is essential to incorporate a mineralization process. In this work, the use of native materials is proposed for the purpose of remineralization, specifically for communities with limited resources under survival conditions where sorbent-based AWH systems may be used.

1.3 Main objective

Water scarcity is a global crisis exacerbated by climate change that highlights the need to explore alternative water sources. AWH technologies have the global potential to meet the basic requirement of 5 litres of drinking water per person per day, as the atmosphere is estimated to contain more water than all the rivers and lakes on the planet combined. However, since AWH water often lacks essential minerals important for health and taste, post-treatment adjustments are required to improve its suitability for human consumption, particularly in underserved communities with limited access to resources.

The main objective of this project is to develop an alternative method to remineralize AWH water using locally available resources, in order to develop a low-consumable system suited to resource-constrained communities under survival conditions. This study seeks to answer questions, such as: what is the optimal balance of essential ions for health and taste that can be achieved through natural substrates? and what is considered suitable for consumption after contact with these materials in terms of basic water quality?

1.4 The thesis plan

Chapter 1 serves as the Introduction, where the research problem is contextualized, and the main objective of this study is presented. It outlines key concepts that are essential for understanding the research framework and that will be further explored in the Literature Review.

Then, *Chapter 2* discusses human water consumption, minerals, and their impact on health. It also introduces the concept of water hardness and its potential link to corrosion, followed by a discussion of current regulations on minimum and maximum hardness levels. The chapter then examines existing mineralization methods, highlighting how Pourbaix diagrams help assess metal leaching capabilities in solution. Additionally, it details the mechanisms and reactions of ions, as well as the solubility of key manufactured materials previously studied in the literature. The economic impact of introducing minerals into water treatment processes is also considered. Finally, the chapter presents the thesis's main research focus, the alternative materials naturally available for mineralization, by exploring their ion exchange capacities and the solubility of their ions when exposed to aqueous solutions.

Chapter 3 recalls the main objective and identifies the specific objectives of the work. It further outlines the methodological approach used to achieve the project's main objective. It provides an overview of the experiments conducted to measure ion concentrations through complexometric titration and atomic absorption spectroscopy, as well as the leaching capacities of different materials. The evaluation parameters include a preliminary assessment of drinking water quality, measuring turbidity, conductivity, UV254 transmission, total dissolved solids ,pH, and dissolved organic carbon levels. Additionally, material characterization was conducted via Inductively Coupled Plasma Mass Spectroscopy (ICP-MS), and determination of the performance of a remineralisation filter available on the market.

Chapter 4 presents a summarized version of the most important results of this master's thesis in the form of a scientific article, submitted to the journal Science of the Total Environment.

Chapter 5 discusses the key results of this research, highlighting the strengths and limitations of using native materials as an alternative mineralization system for remote communities under survival conditions. Additional results not included in the scientific article are also presented.

Chapter 6 provides the final conclusions of this research and explores recommendations for future studies, including a more comprehensive evaluation with microbiological testing to develop a protocol for selecting the best candidate material for water mineralization. It suggests further investigation into techniques such as the pyrolysis of natural samples at higher temperatures, the potential of mixed bed systems, and continuous column testing. These findings contribute to the scientific advancements in the field and open discussions on new research directions related to this master's project.

CHAPTER 2 LITERATURE REVIEW

2.1 Water intake

Understanding water consumption patterns is important because it helps determine the amount of nutrients consumed through water. The WHO estimates a daily intake of 2 liters for adults, based on a person's daily fluid requirements, which roughly matches essential water losses due to sweating from physical activity and environmental conditions [21]. **Table 2.1** shows an estimate of the hydration requirements in 3 different situations for children or adults.

Air temperature, wind speed, humidity, sex, age, type and intensity of exercise, and even clothing are all factors that influence sweat rate. In intense conditions, sweat loss can reach up to 4 liters per hour [26].

Exceeding the kidney's excretory and dilution capacity can lead to water intoxication and hyponatremia, a condition where sodium levels drop too low. Approximately 13 liters per day is the estimated maximum safe water intake to prevent serum hypo-osmolarity [27]. However, no single upper limit can be established without considering individual and environmental factors.

It is estimated that about one-third of daily fluid intake comes from food, either naturally present or added during preparation [28]. The rest comes from drinking water and other beverages. Availability, ambient temperature, taste, variety, beverage temperature, proximity, and even packaging influence total water consumption [29]. The amount and type of water consumed are linked to the intake of the elemental elements and potentially harmful contaminants present.

The significant amounts of water required highlight the challenge faced by communities experiencing water scarcity. With approximately two-thirds of the world's population experiencing water scarcity for at least one month each year [3], it can be inferred that these populations are unable to meet their basic water needs during this time.

Table 2.1. Estimates hydration requirements [21]

Situation	Unit	Children	Female at the age of adult	Male at the age of adult
Average conditions	L/day	1	2.2	2.9
Physical activity in high temperatures		4.5	4.5	4.5
Overall requirement during lactation/pregnancy		—	3.3 — 4.8	—

2.2 Minerals in water

Minerals are known to be essential for humans: these elements have impact on the structure of bones and cell membranes, water and electrolyte balance, oxygen carrying capacity and hormonal functions. Normally, they are divided into macronutrients and micronutrients based on the amount that the body needs to maintain its essential functions: macronutrients include calcium, phosphorus, magnesium, sodium, potassium and chlorine; and micronutrients include iron, iodine, zinc, selenium, cobalt, chromium, copper, fluorine, molybdenum and manganese [30].

Drinking water can naturally contain some essential minerals such as calcium, magnesium, selenium, fluoride, and zinc. As shown in **Table 2.2**, the moderate or low bioavailability of essential minerals in some or most water supplies reflect the typical estimated values, which may range from low, variable or moderate to high occurrence. For example, calcium shows variable occurrence in water and is moderately bioavailable in some supplies, with a typical concentration of 26 mg/L. In contrast, chromium has a low occurrence and low bioavailability in most supplies, with a typical value of 0.0085 mg/L, though it should be noted that its toxicity depends on its oxidation state [31]

Minerals may also be present due to chemical addition or leaching from pipes, as in the case of copper or iron. However, water supplies vary greatly in their mineral content, and in most cases, they provide only small amounts of essential nutrients. Many people choose bottled water because they believe it is a healthier option than tap water, as it is believed to be more closely monitored and to contain essential minerals. However, not all bottled water has the same mineral content, which varies just as much as it does in tap water. In addition, bottled water carries its own risks; its safety can be compromised if it is not stored or handled properly [32,33].

Table 2.2. Essential minerals in water supplies [21,34,35]

Bioavailability	Occurrence and typical** level in water		
	Low	Variable or Moderate	High
Moderate amounts in some supplies	0.240 mg Fe*/L	26 mg Ca*/L	28 mg Na/L
		6.25 mg Mg*/L	21 mg Cl/L
		< 0.200 mg Zn*/ L	0.4 mg F/L
		0.100 mg Cu*/L	0.001 mg Se*/L
Low amounts in most supplies	0.0085 mg Cr/L	0.025 Mn mg/L	2.15 mg K*/L
			0.1 – 0.3 mg B*/L
			< 0.200 mg Mo/L
			0.12 mg P/L
			0.004 mg I*/L

(*)Suboptimal intakes and/or deficiencies present in a certain number of countries.

(**)Typical is understood as an estimate of what is usually found (averages or ranges). An accurate general ion concentration is hard to calculate through statistical methods due to the way water composition data is reported.

The potential health benefits of drinking water also depend on water consumption, which varies according to behavior and environment. People who drink the most water tend to include young children between 13 and 23 months of age, whose recommended daily intake ranges from 1100 to 1200 mL, as well as individuals living in hot climates, and those engaged in strenuous activities [36,37].

Element levels to be achieved in drinking water vary across countries, with some WHO guideline values in place. Fluoride has a recommended range of 0.4–1.5 mg/L, while chloride is set at 250 mg/L and adopted by 100 countries. For minerals like sodium (100–400 mg/L), sulfate (50–800 mg/L), and potassium (1.5–50 mg/L), no WHO limits exist, but many nations have established their own standards [38].

Calcium and magnesium are nutrients that are present in drinking water in noteworthy concentrations. Both play an important role in bone health, and magnesium also contributes to cardiovascular function [39]. Fluoride is well known for its effectiveness in preventing dental caries [40], while sodium, an important electrolyte, is involved in the maintenance of fluid balance and is lost through excessive sweating [41]. Copper supports antioxidant function, iron utilization, and cardiovascular health [42], whereas selenium plays a key role in antioxidant defense and immune system support [43]. Although potassium is essential for various biochemical processes, playing a role in modulating cell volume and osmolality [44], it is typically found in low levels in drinking water [34].

2.3 Water hardness

When water with high concentrations of bicarbonate and Calcium is heated, a solid calcium carbonate precipitate tends to form. This buildup is particularly problematic in boilers and hot water pipes, as it can obstruct the flow and reduce efficiency. The term water hardness likely originates from this phenomenon, as early observers noticed the blockages caused by these mineral deposits [45,46], as described in the **Equation 2.1.**

$$Ca^{2+} + 2HCO_3{}^{-} \overset{\Delta}{\rightarrow} CaCO_3 \downarrow + CO_2 \uparrow + H_2O \qquad \mathbf{(2.1)}$$

In Canada, water hardness is measured in milligrams of $CaCO_3$ per litre. Worldwide, however, water hardness is expressed in various units. In some places, it is often measured in grains per gallon (gr/gal), where 1 gr/gal equals 17.1 mg/L of $CaCO_3$. In Germany, the hardness degree (dH) is commonly used, with 1 dH corresponding to 17.85 mg/L of $CaCO_3$, while in France, the French hardness degree (°f) represents 10 mg/L of $CaCO_3$ per unit. Another way to express hardness is in milliequivalents per liter of CaO or $CaCO_3$ [45].

Hardness indicates the concentration of multivalent metal cations, like calcium (Ca^{2+}) and magnesium (Mg^{2+}), which determine whether water is hard or soft. In some cases, trace amounts of ferrous iron and manganese also contribute to hardness [47]. It is also possible to measure hardness directly through chemical analysis, like Complexometric Titration, Inductively Couple Plasma Mass Spectrometry (ICP - MS), Atomic Absorption Spectroscopy (AAS) or Ion Chromatography (IC).

2.3.1 Effect of hardness in human consumption

Hard water contributes calcium and, in some cases, magnesium to the diet. However, their levels can vary considerably depending on the water source and individual consumption. Consumed at moderate levels of hardness (60 to 120 mg $CaCO_3$ /L), water can provide a significant portion of daily dietary needs. According to the WHO, drinking water can contribute around 5–20% of a person's daily mineral intake, while the majority is obtained from food [21].

When used for cooking, soft water can lead to a greater loss of essential minerals from food like meat, vegetables, cereals and potatoes. This occurs because the low mineral content of soft water creates a chemical imbalance, causing minerals from the food to dissolve more readily into the cooking water. In addition, water that lacks minerals can lead to nutrient losses in beverage and food production, potentially lowering the calcium, magnesium, and other essential nutrient content in the final products [48].

According to Health Canada, the essential role of calcium and magnesium in nutrition is well recognized, and their consumption across a wide range is not known to have any harmful effects on the general public's health [49]. Additionally, there is suggestive evidence that links calcium and magnesium intake to potential benefits for various health conditions, such as a lower risk of stroke, very low birth weight, possibly certain cancers, childhood bone fractures, pregnancy complications, kidney stones, cognitive decline in the elderly, and hypertension [21].

Consumption of low-mineral water has been correlated with reduced cardiometabolic health, likely due to inadequate intake of beneficial minerals [50]. Epidemiological studies have reported an association between total drinking water hardness and cardiovascular disease mortality [51–55]. However, no definitive scientific consensus exists regarding the connection between water hardness and health.

Adding magnesium and calcium to water with low mineral concentrations would offer health benefits to drinking water. For instance, the addition of calcium and magnesium carbonates to mineralise water is a common post-treatment technique to stabilise the ionic composition of water [56]. Increasing the daily intake of these elements can be achieved through various water conditioning processes.

concentrations also impact the organoleptic properties of the water, i.e. the taste of water [57–62]. One study determined that water taste is influenced by cations (calcium, magnesium, sodium) and anions (nitrate, sulfate, chloride), which affect how pleasant the taste is perceived to be. Additionally, a lower perception of freshness and thirst-quenching ability is associated with low Total Dissolved Solids (TDS) levels, particularly below 100 mg/L [63]. Although taste is a factor that may be subjective to what the consumer is used to.

2.3.2 Water Hardness Regulations and Standards

The establishment of regulations setting minimum levels for calcium and magnesium reflects a growing recognition of their importance in drinking water. **Table 2.3** provides ranges of recommended and minimum required levels of essential minerals from various sources.

Table 2.3. Minimum and recommended levels of Ca^{2+}, Mg^{2+}, Total Dissolved Solids (TDS) in some countries of the European Union (EU) [24,38]

Parameter	TDS (mg/L)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)
Minimum in demineralized water	100	30	10
Recommended concentration for health	200 ─ 500	40 ─ 80	20 ─ 40

Three EU member states have set minimum concentrations for magnesium, while six have done so for calcium. Hardness is a concern for more countries, with twelve establishing a minimum threshold (**Figure 2.1**).

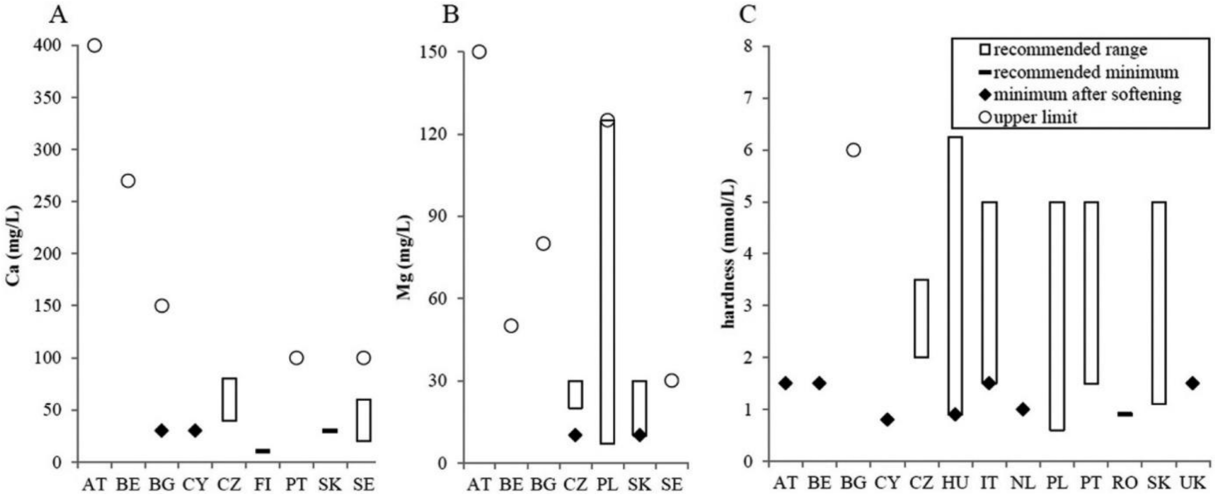


Figure 2.1. Comparison of recommended ranges and regulatory limits for drinking calcium (A), magnesium (B), and hardness (C) in drinking water across different EU countries, covering technical guidelines and legal regulations. Reproduced from Lesimple et al., 2020[38][c]

There is no recommendation or standard in Canada regarding a minimum hardness level. However, the latest guidelines highlight the importance of exploring the hardness and the role of calcium and magnesium in drinking water, though no specific value is established [64].

2.3.3 Hardness and Corrosion

Corrosion is the process by which metallic materials deteriorate through chemical and electrochemical reactions. Corrosion occurs as, over time, materials attempt to return to their natural state, this brings a lower energy state and achieve greater thermodynamic stability [65].

Potable water distribution plays a vital role in societal infrastructure. However, as water moves through the primary distribution pipes and service lines, its quality tends to degrade [66]. The corrosion that occurs within distribution systems leads to three interconnected challenges:

- Sarin et al., 2004 [67] say that iron pipes typically undergo mass loss due to oxidation, forming iron-containing deposits or ferrous species .
- Hussein Farh et al., 2023 [68] mention that deposits can accumulate and grow into larger particles, leading to a reduction in the water-carrying capacity and an increase in head loss.

---

[c] Reproduced from Alain Lesimple, Farah Ejaz Ahmed, Nidal Hilal, Remineralization of desalinated water: Methods and environmental impact, Desalination, Volume 496, 2020, 114692, ISSN 0011-9164, https://doi.org/10.1016/j.desal.2020.114692, with permission from Elservier

As the deposits build up, they diminish the hydraulic capacity, which results in more difficulty maintaining the desired flow rate due to the clogging of the pipes system

- McNeill & Edwards, 2001 [69] state the negative effects on the aesthetic quality of water due to the release of soluble or corrosion particles or by-products.

The formation of corrosion deposits in iron pipes is strongly influenced by factors such as alkalinity, aqueous ions, oxidation-reduction potential, and pH. These conditions shape the physicochemical properties of the deposits and contribute to the development of compounds like goethite $(\alpha - FeOOH)$, akageneite $(\beta - FeOOH)$, lepidocrocite $(\gamma - FeOOH),$ and magnetite (Fe_3O_4) [70].

Failures in distribution system pipes and household plumbing can lead to economic and cost-related implications [71]. Corrosion poses health and economic risks that may go unnoticed without proper monitoring of the distribution network. Ensuring water stability by regularly monitoring the balance of chemical and physical properties that prevent excessive corrosion is a key strategy for reducing operational maintenance [72]. To assess the corrosive nature and potential formation of hard, crusty deposits; the Larson-Skold Index (LSI) was developed to determine the water's tendency for ferrous corrosion[73], values ranging from -0.5 to 0.5 indicates conditions that span from slight corrosion, trough chemical equilibrium, to slight scaling [74]. Additionally, the calcium carbonate deposition capacity is obtained from the calcium carbonate precipitation potential (CCPP) [75].

Soft water can be corrosive to distribution systems, which could cause problems with water colour [76] and infrastructure problems. For desalinated water, recommended quality criteria have been established, including a pH value between 7.5 and 8.5, alkalinity above 80 mg/L as $CaCO_3$, CCPP between 3 and 10 mg/L, , and calcium concentration between 80 and 120 mg/L [77]. Historically, this hardness level range was chosen as it provides an acceptable balance between corrosion and incrustation [49]. However, this balance is still to be confirmed.

The corrosion impacts on cast iron pipes were carried out in a study with the exposure of three different water profiles: groundwater (GP), surface water (SP), and blended water (BP), collected from three sites across Xuchang and Zhengzhou in Henan Province, China (**Figure 2.2**). The pipe sections were then transported to a treatment plant near the Danjiangkou Reservoir (Hubei Province, China). One of the objectives was to examine the relationship between water hardness and iron release (to determine the form of corrosion). The study also considered other factors, including corrosion scale evolution, changes in the bacterial community and dissolved oxygen consumption (ΔDO) [78].

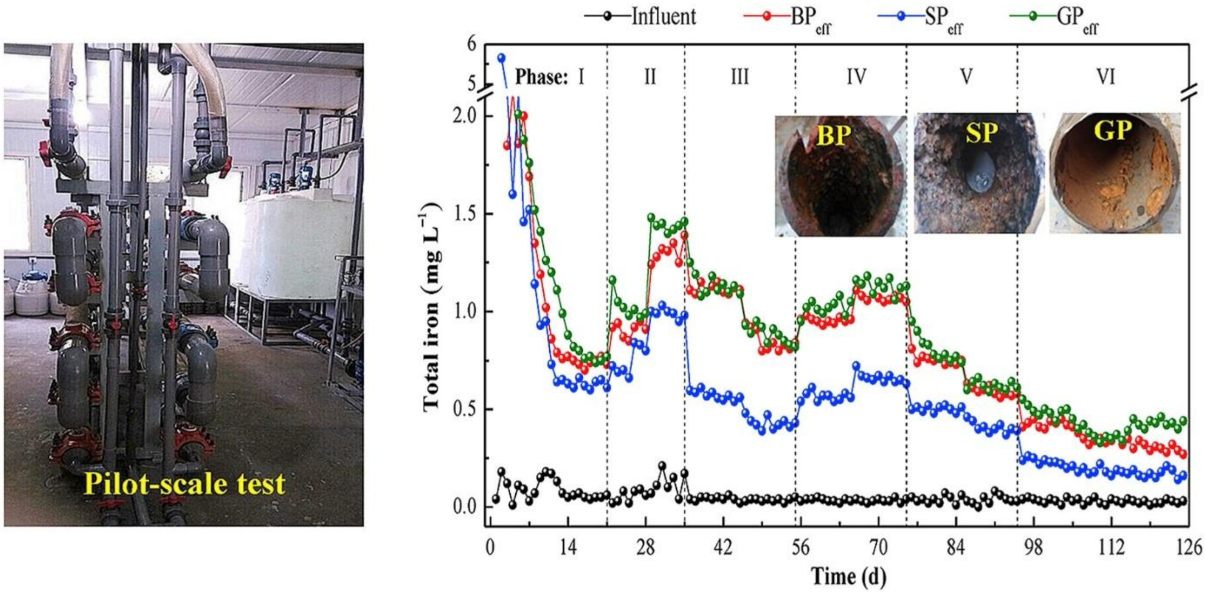


Figure 2.2. Fluctuation of Total Iron Concentration (TIC) over time in the inlet and outlet of Blended water (BP), Surface water (SP), and ground water (GP), with a flow rate of 0.16 m^3/d and pipe systems measuring 20 m in length and 100 mm in inner diameter. Reproduced from Hu et al., 2018 [78].[d]

In Phase I, desalinated water (DSW) with an LSI of 0.26 was pumped into the systems, resulting in a high initial effluent TIC that rapidly decreased. The relatively weak corrosion observed in DSW, indicated by its low LSI, suggests a less corrosive nature.

Phase II saw the addition of chloride ions (Cl^-), which significantly increased both TIC and LSI, emphasizing their role in promoting corrosion. In Phase III, an alkalinity increase led to a reduction in iron release, with higher alkalinity promoting the precipitation of carbonate. Phase IV involved sulfate ions (SO_4^{2-}), which slightly promoted iron release by reacting with iron oxides.

In Phase V, a key finding was that increasing calcium hardness reduced iron release, as higher hardness levels enhanced calcium carbonate precipitation, lowering the effluent TIC and mitigating

---

[d] Reproduced from Jun Hu, Huiyu Dong, Qiang Xu, Wencui Ling, Jiuhui Qu, Zhimin Qiang,Impacts of water quality on the corrosion of cast iron pipes for water distribution and proposed source water switch strategy, Water Research,Volume 129, 2018, Pages 428-435, ISSN 0043-1354, https://doi.org/10.1016/j.watres.2017.10.065, with permission from Elservier

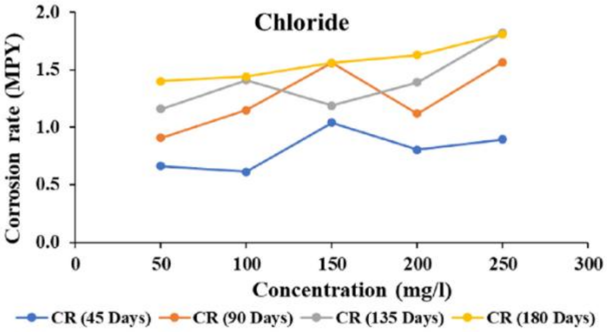
corrosion. This phase highlights the crucial role of hardness in controlling corrosion in water distribution systems.

Finally, in Phase VI, a sequence of disinfectants was applied, leading to varied effluent TIC patterns across the systems, illustrating the complex effects of microbial and chemical interactions on iron release. The study concludes that the formation of siderite ($FeCO_3$) and calcite ($CaCO_3$) due to increased alkalinity and calcium hardness in the experiments confirmed that iron released was inhibited by calcium hardness and alkalinity.

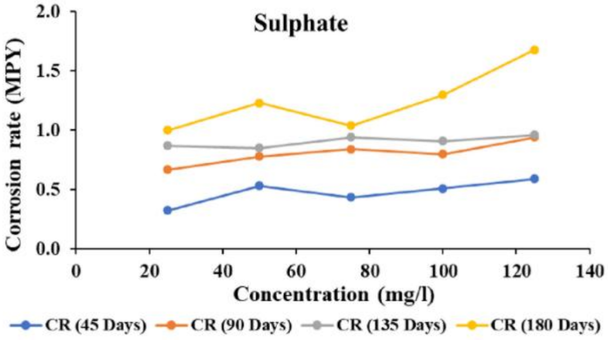
Another study on corrosion rate modeling in drinking water distribution networks investigated the impact of water hardness on corrosion rate, along with other parameters such as: chloride, sulfate, alkalinity, pH, calcium ion concentration. Synthetic aqueous solutions were used to analyse the rate at which corrosion occurred [79].

The corrosion rate was observed to rise as chloride or sulfate concentrations increase (**Figure 2.3** a & b), as these compounds react with metals and prevent protective oxides from forming. In contrast, the corrosion rate decreases as hardness or alkalinity increases, as they promote the formation of protective scales such as calcium carbonate. Additionally, pH affects the corrosion rate: corrosion is faster in acidic environments, while it decreases under neutral or alkaline conditions. High TDS increases conductivity, which in turn enhances corrosion due to the rise in corrosive currents (**Figure 2.3**, section c, d, and f).

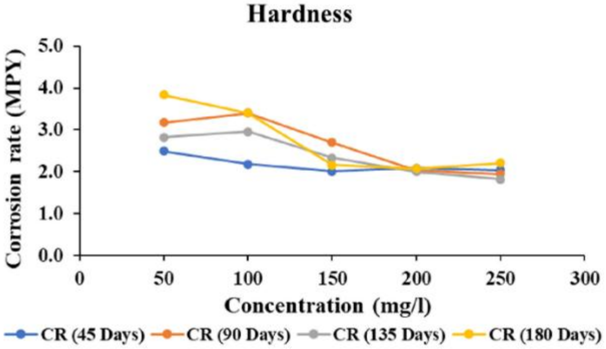
a.


Chloride
Corrosion rate (MPY)
0.0
0.5
1.0
1.5
2.0
0
50
100
150
200
250
300
Concentration (mg/l)
CR (45 Days)
CR (90 Days)
CR (135 Days)
CR (180 Days)

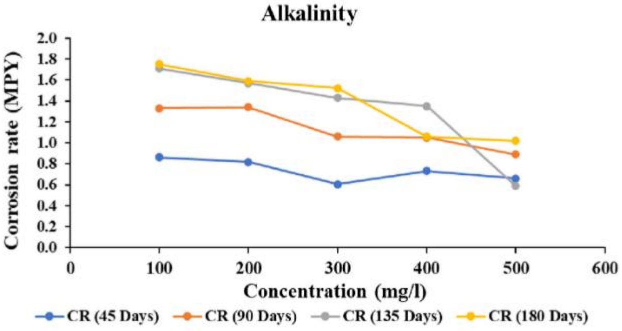
b.


Sulphate
Corrosion rate (MPY)
0.0
0.5
1.0
1.5
2.0
0
20
40
60
80
100
120
140
Concentration (mg/l)
CR (45 Days)
CR (90 Days)
CR (135 Days)
CR (180 Days)

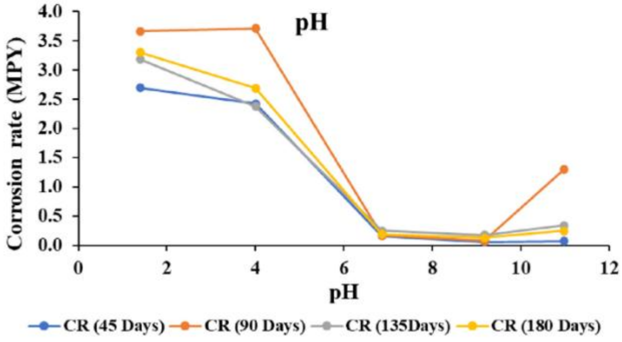
c.


Hardness
Corrosion rate (MPY)
0.0
1.0
2.0
3.0
4.0
5.0
0
50
100
150
200
250
300
Concentration (mg/l)
CR (45 Days)
CR (90 Days)
CR (135 Days)
CR (180 Days)

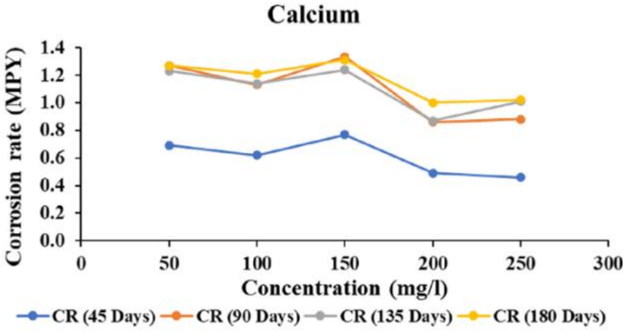
d.


Alkalinity
Corrosion rate (MPY)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
0
100
200
300
400
500
600
Concentration (mg/l)
CR (45 Days)
CR (90 Days)
CR (135 Days)
CR (180 Days)

e.


pH
Corrosion rate (MPY)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
0
2
4
6
8
10
12
pH
CR (45 Days)
CR (90 Days)
CR (135Days)
CR (180 Days)

f.


Calcium
Corrosion rate (MPY)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
0
50
100
150
200
250
300
Concentration (mg/l)
CR (45 Days)
CR (90 Days)
CR (135 Days)
CR (180 Days)

g.

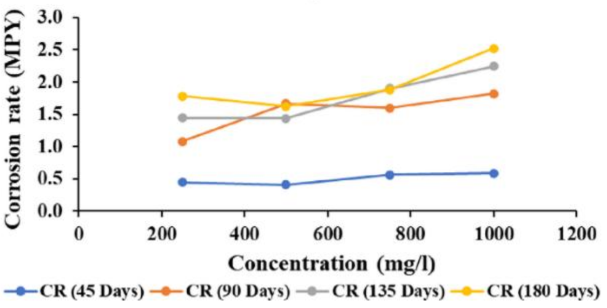

TDS
Corrosion rate (MPY)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0
200
400
600
800
1000
1200
Concentration (mg/l)
CR (45 Days)
CR (90 Days)
CR (135 Days)
CR (180 Days)

Figure 2.3. Graph of corrosion rate vs concentration for different solutions, including chloride (a), sulphate (b), hardness (c), alkalinity (d), pH (e), calcium (f), TDS (g). Reproduced from Kumar et al., 2023 [79][e]

2.4 Mineralization

2.4.1 Method a: Direct dosage of chemicals

Direct dosing of chemicals into demineralized water offers simplicity, flexibility in terms of the quality of the produced water, and low investment costs, but only if it concerns small-capacity water treatment plants [80]. The compounds used in this process involves the sodium carbonate (Na_2CO_3), calcium chloride ($CaCl_2$), carbon dioxide (CO_2) and hydrated lime ($Ca(OH)_2$) [81]

Worldwide, the most used dosing technique is the combination of CO_2 with excess $Ca(OH)_2$ [82], where demineralized water is remineralized with calcium and bicarbonate in a 1:1 ratio, as shown in **Equation 2.2.**

$$2\,CO_2 + Ca(OH)_2 \rightarrow \,Ca^{2+} + 2\,HCO_3{}^{-} \qquad (\mathbf{2.2})$$

$Ca(OH)_2$ is typically introduced as a lime slurry into saturators. These saturators are thickener-clarifier tanks designed to facilitate the dissolution of lime particles. This is necessary because lime does not dissolve easily and can generate undesirable turbidity values [83].

Different chemical combinations have been explored for remineralization, including $CaCl_2/NaHCO_3/Na_2CO_3$, $CaCl_2/Na_2CO_3$, $CO_2/Ca(OH)_2$, and $CaCl_2/NaHCO_3$. However, three of these mixtures have the disadvantage of increasing sodium and chloride levels [83], According to the Texas Water Development Board, chloride can be problematic if concentrations exceed the 250 mg/L limit [84] . A simpler approach for stabilization in the brackish water desalination process is the use of NaOH. This method is widely adopted as it not only helps in stabilization but also to protect metal pipes and distribution systems from corrosion, often in combination with corrosion inhibitors [85].

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[e] Reproduced from Kumar, S., Singh, R. & Maurya, N.S. Modelling of corrosion rate in the drinking water distribution network using Design Expert 13 software. Environ Sci Pollut Res 30, 45428–45444 (2023). https://doi.org/10.1007/s11356-023-25465-z with permission from Springer Nature.

2.4.2 Method b: Blending of hard water with a soft effluent

The proportion of source water blended with demineralized water typically ranges from below 1% to a maximum of 10%, influenced by taste and corrosion concerns. Low-salinity brackish water and seawater can serve as sources, seawater is generally kept at 1% or lower. If the proportion increases, bromide in the water may react with remaining disinfectants during distribution and storage periods [56,86].

The blending is possible if the source water meets the high-quality standards and has undergone proper pre-treatment. If exposed to organic matter, filtration with activated carbon is advised to eliminate potential contaminants [56]. To enhance the flexibility and reliability of the water supply, it is common practice to mix demineralized water with potable water from other sources or groundwater.

2.4.3 Method c: Mineral dissolution

Because it is significantly more affordable to handle and nearly twice as cost-effective as lime [56], limestone is widely used as a substrate for remineralization. The process begins with demineralized water being acidified using H_2SO_4 or CO_2 to bring the pH below 4.5, after which it comes into contact with a compact bed of calcite granules. As calcite dissolves in the presence of CO_2, it contributes to the alkalinity of the carbonate and provides calcium ions. This is shown in the **Equation 2.3**, where calcite dissolves in the presence of CO_2:

$$CaCO_3 + CO_2 + H_2O \rightarrow Ca^{2+} + 2\,HCO_3{}^{-} \qquad \mathbf{(2.3)}$$

In theory, the use of calcite leads to the same remineralization products: Ca^{2+} and HCO_3^-, with only half the CO_2 consumption. However, in practice, 65% to 85% of the CO_2 reacts in the calcite process [87]. In limestone contactors, the reaction is slower compared to the liquid lime process and the reaction does not fully complete, requiring neutralization of the remaining CO_2 with Na_2CO_3 or NaOH [88]. Moreover, in method A, the amount of $Ca(OH)_2$ typically used is approximately 70% to 80% of the equivalent mass of calcite required [87].

H_2SO_4 is an alternative to CO_2 to promote limestone dissolution. The ratio of reagents varies depending on the acid concentration, resulting in two commonly expressed reactions:

Equation 2.4 shows the molar ratio (2:1)

$$2\,CaCO_3 + H_2SO_4 \rightarrow\ Ca^{2+} + 2\,HCO_3{}^{-} + CaSO_4 \qquad \mathbf{(2.4)}$$

Equation 2.5 presents the molar ratio (1.55:1)

$$1.55\,CaCO_3 + H_2SO_4 \rightarrow\ 1.55\,Ca^{2+} + 1.1\,HCO_3{}^{-} + 0.45\,H_2CO_3 + SO_4{}^{2-} \qquad \mathbf{(2.5)}$$

The H_2SO_4 process has a faster reaction kinetics, which allows for a smaller size of the calcite dissolution contactors. However, the reaction results in a calcium-bicarbonate ratio that generates excess of ions and an elevated sulfate concentration in the treated water These conditions can promote scale formation and, if sulphate levels exceed the recommended upper limit of 500 mg/L, they can cause taste impairment in the water [89].

2.5 Pourbaix diagrams as a tool for leaching capacity assessment

Pourbaix diagrams, also known as potential-pH diagrams, illustrate the electrochemical stability of an element in a specific environment. These plots, which depict potential as a function of pH, are valuable tools for determining the conditions under which a metal may undergo leaching. Understanding these conditions is also essential when considering water remineralisation by mineral dissolution, as certain materials can release or retain ions depending on pH conditions.

Pourbaix diagrams provide insights into the thermodynamic stability of various metal phases that can exist in a variety of conditions. However, it is important to mention that Pourbaix diagrams are equilibrium diagram, and as such do not account for reaction kinetics nor predict the rate at which leaching reactions may occur.

The regions within these diagrams represent equilibrium states between different species, governed by both pH and electrochemical potential. A key feature of all Pourbaix diagrams is the presence of two diagonal lines with a slope of -0.059 V/pH, spanning a potential range from 0 to 1.23 V. This region defines the stability of water; above it, oxygen evolution occurs, while below it, hydrogen evolution takes place.

Different line orientations in the diagram indicate distinct equilibrium conditions. Horizontal lines correspond to redox reactions independent of proton concentration, as protons do not participate in these reactions. Vertical lines represent acid-base equilibria where oxidation states remain unchanged. Sloped lines, on the other hand, indicate equilibria involving both proton and electron transfer, meaning the electrochemical potential varies with pH. This relationship can be described mathematically using the Nernst equation at 25°C, described in **Equation 2.6.**

$$\Delta E = \Delta E^{\circ} - \frac{0.059}{n_e} V \log_{10}(Q) \qquad (\mathbf{2.6})$$

which can define the pH dependence of electrochemical potential as follows in the **Equation 2.7**:

$$E_{H^+} = E^{\circ}{}_{H^+} - 0.059\ pH \qquad (\mathbf{2.7})$$

Where, ΔE: Cell potential under non-standard conditions, ΔE°: Standard cell potential and conditions (298K, 1 atm, 1 M), n_e : Number of moles of electrons transferred in the redox reaction, V: volts, Q: reaction quotient, $E_H{}^+$: Hydrogen electrode potential under non-standard conditions, and $E^{\circ}{}_H{}^+$: Standard hydrogen electrode potential.

Pourbaix diagrams typically exhibit three distinct stability regions; these regions provide essential insights into the stability of metals in different electrochemical environments, serving in the assessment of their susceptibility to degradation.

- *Immunity:* In this region, the metal remains in its solid state and does not undergo corrosion, indicating thermodynamic stability against dissolution.
- *Corrosion (Leaching):* This region corresponds to conditions where the metal exists in a soluble ionic form, making dissolution thermodynamically favorable. Under these conditions, metal ions readily enter the solution.
- *Passivation:* In this region, the formation of insoluble metal oxides or hydroxides occurs, creating a protective layer that inhibits further corrosion.

As previously stated, Ca^{2+} and Mg^{2+} ions are essential elements in drinking water, influencing both water stability and mineral content. Within the water stability region, calcium remains in dissolved form, meaning that solid calcium remains stable in contact with water across all pH levels. However, depending on the electrochemical potential, insoluble calcium phases may precipitate (**Figure 2.4**).

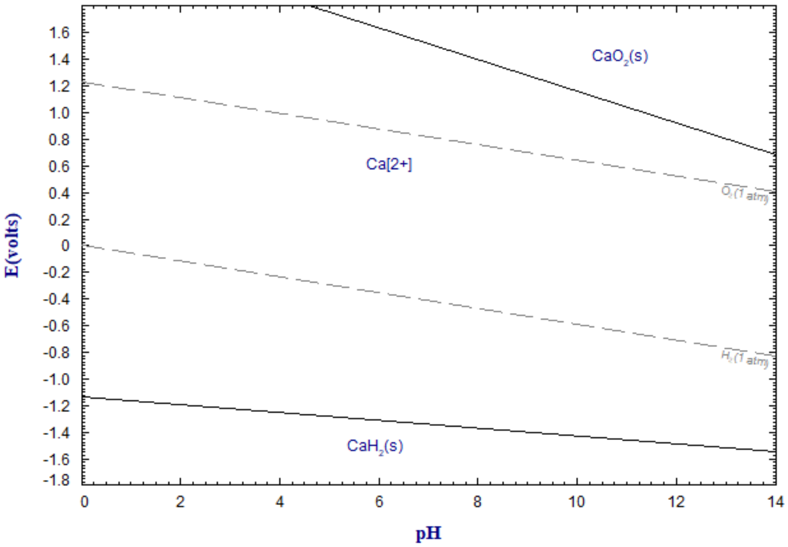

Figure 2.4. Calcium and Water Equilibrium at 298.15 K with a Molality of 1.0e-6 mol/kg, generated using FactSage Education 8.3 (FactSageEdu).

Magnesium, in contrast, can exist as both dissolved ions and as an oxide within the water stability region. Unlike calcium, magnesium is inherently unstable in contact with water, regardless of pH or potential. Under specific conditions, magnesium may either dissolve into the solution (leaching) or form a passivating layer (**Figure 2.5**).

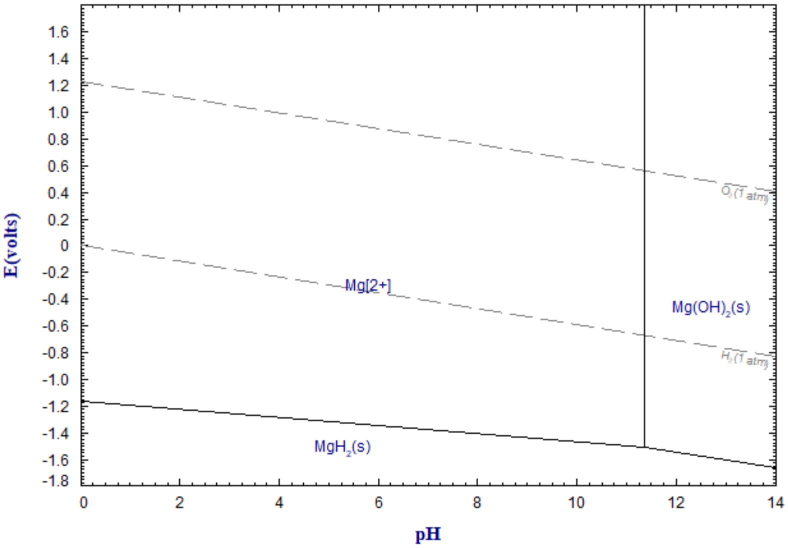

Figure 2.5. Magnesium and Water Equilibrium at 298.15 K with a Molality of 1.0e-6 mol/kg, generated using FactSage Education 8.3 (FactSageEdu).

2.6 Calcium and Magnesium Reactions in Water

When metals react with cold water, they typically form their corresponding hydroxides. Calcium, for example, reacts aggressively, producing heat in an exothermic reaction [90]. This results in the formation of $Ca(OH)_2$, which appears as a whitish precipitate. Since $Ca(OH)_2$ is poorly soluble in water, the solution becomes alkaline, and hydrogen gas bubbles are released [91]. Despite its vigorous nature, calcium's reaction with water is slower compared to some other metals. Magnesium, on the other hand, reacts very mildly with cold water. Over time, hydrogen gas bubbles could appear, and the formation of $Mg(OH)_2$ takes place[92]. However, the reaction stops quickly because the $Mg(OH)_2$ formed is nearly insoluble, creating a passivation layer at the surface of pure magnesium that prevents further interaction with water [90]. The reactions previously described are shown in **Equations 2.8, 2.9**:

$$Ca_{(s)} + 2\, H_2O_{(g)} \rightarrow\; Ca(OH)_{2\,(aq)} + H_{2\,(g)} \qquad \mathbf{(2.8)}$$

$$Mg_{(s)} + 2\, H_2O_{(l)} \rightarrow\; Mg(OH)_{2\,(s)} + H_{2\,(g)} \qquad \mathbf{(2.9)}$$

2.7 Commercial options for mineralization

This section explores commercial remineralization options, focusing on the use of Calcite to improve the quality of demineralized water.

As a major component of limestone, calcite is one of the most prevalent minerals in the environment. It represents the most common crystalline form of $CaCO_3$ and is the most thermodynamically stable under typical conditions, including ambient temperature and atmospheric pressure. Given its extensive distribution, calcite plays a vital role in surface interactions within environmental and geochemical systems.

One of the most widely used remineralization techniques, as mentioned earlier, involves dissolving $CaCO_3$ by passing demineralized water that was previously acidified through a packed bed that contains limestone. The limestone is in the form of grains of a few millimeters in size and consist mostly of pure calcite. This process's efficiency is determined by how easily calcite dissolves in water, as measured by the solubility product constant (Ksp) that shows the equilibrium concentration of dissolved ions in a saturated solution, indicating the compound's dissolution tendency. For calcite, the Ksp is equal to 5 × 10^{-9} mol^2/L^2 at 25°C, and at pH value of 5.6, its dissolution rate is approximately 10^{-10} $mol/(cm^2 \cdot s)$

The interaction between calcite, carbon dioxide and water is essential in shaping geochemical conditions, including pH and alkalinity, in environments such as lakes, soils, seawater and aquifers. This effect is mainly due to the buffering ability of carbonic acid ions. As shown by Herberling et al., 2014 [93], the system is mainly regulated by four key reactions, as shown in the following reaction scheme from **Equation 2.10– 2.13.**

(1) Dissolution or formation of calcite:

$$CaCO_{3\,(s)} \leftrightarrow Ca^{2+} + {CO_3}^{2-} \quad log_{10}K_{sp}(Cc) = -8.48 \qquad \mathbf{(2.10)}$$

Where, Ksp (Cc) = Solubility product of calcite

(2) and (3) Reactions of protonation and deprotonation in carbonate species that contribute to the buffering capacity of calcite.

$${CO_3}^{2-} + H^+ \leftrightarrow {HCO_3}^- \quad log_{10}K = -10.33 \qquad \mathbf{(2.11)}$$

$$H_2CO_3 + H_2O \leftrightarrow {HCO_3}^- + H^+ \quad log_{10}K = 6.35 \qquad \mathbf{(2.12)}$$

(4) Reaction of carbon dioxide in water:

$$CO_{2\,(g)} + H_2O \leftrightarrow {HCO_3}^- + H^+ \quad log_{10}K = -7.82 \qquad \mathbf{(2.13)}$$

The thermodynamic constants previously presented are based on standard temperature and pressure, as well as a zero ionic strength condition.

Since $CaCO_3$ is a commonly used medium in treatment processes, there is also another well-documented material to consider. Although the dissolution of calcite releases Ca^{2+} ions into the treated water, the growing evidence in recent years has emphasized the significance of Mg^{2+} for human health in drinking water. To address this, brucite or magnesium oxide (MgO), commercially available under the name of Corosex™ (with 98% purity) can be used to add Mg^{2+} ions into the effluent. Additionally, MgO contributes to pH adjustment as it quickly dissolves and hydrates to form $Mg(OH)_2$.

MgO is an inorganic compound that ranges in color from pale gray to clear and is rarely found in its pure form in nature. Its physical and chemical characteristics largely depend on the precursor used during synthesis. Commonly, MgO is produced from magnesite ($MgCO_3$) or extracted from seawater and other brines rich in magnesium chloride ($MgCl_2$).

When MgO comes into contact with water, it undergoes an alkaline reaction, forming $Mg(OH)_2$, as shown in **Equation 2.14**. As Rocha et al., 2024 [94] states, this process is influenced by mechanisms such as dissolution, hydration, precipitation, nucleation, and crystal growth, which contribute to its overall behavior.

$$MgO_{(g)} + H_2O \rightarrow Mg(OH)_{2\,(s)} \qquad \mathbf{(2.14)}$$

In water treatment processes where temperatures remain below 90 °C, an alternative reaction mechanism has been suggested. This reaction consists of sequential dissolution and precipitation stages, with variations observed in kinetic models and intermediate reaction pathways. Rocha et al., 2024 [94] provided a summary of main reactions, which are represented **in Equations 2.15, 2.16** as follows:

1. Water molecules adsorbs to the surface while diffuses inside the porous structure of MgO.

2. As the oxide dissolves inside the particles, it gradually leads to changes in porosity over time.

$$MgO_{(s)} + H_2O_{(l)} \rightarrow Mg^{2+} + 2\,OH^- \qquad \mathbf{(2.15)}$$

3. The surface of the MgO serve as the site for supersaturation, nucleation, and growth of $Mg(OH)_2$.

$$Mg^{2+} + 2\,OH^- \rightarrow Mg(OH)_{2\,(s)} \qquad \mathbf{(2.16)}$$

In non-acidified soft water, the dissolution of MgO is constrained by its low equilibrium solubility, reaching a maximum magnesium ion concentration of 34 mg/L or 84 mg/L as $CaCO_3$/L [4]. However, introducing CO_2 to acidify the inlet solution can enhance the rate and extent of MgO dissolution.

The solubility and ion release of $CaCO_3$ and MgO in water are closely linked to the presence of dissolved inorganic carbon species, particularly HCO_3^-, which forms when $NaHCO_3$ is added to the system, as shown in the previously discussed carbonate equilibrium equations. This added alkalinity simulates conditions with elevated dissolved CO_2, enhancing the dissolution of both materials. $CaCO_3$, is more responsive to increased HCO_3^- concentrations, resulting in more effective pH correction and calcium release. While MgO also dissolves more readily under higher alkalinity, its pH control remains more stable [95]. In systems without added $NaHCO_3$, representing lower CO_2 availability, both commercial materials exhibit limited dissolution. These observations highlight the importance of CO_2 availability, through alkalinity adjustment, to optimize remineralization via mineral dissolution in demineralized waters such as those from AWH technologies

MgO and $CaCO_3$ play a key role in mineralizing water that lacks dissolved divalent metal ions (Me^{2+}), when brucite and calcite dissolve, they promote the formation of metal oxides (MeOx). The figure **Figure 2.6** shows several key processes which occur within these systems: (1) MgO undergoes rapid hydration, forming $Mg(OH)_2$, while (2) Me^{2+} ions are captured through sorption-coprecipitation or possibly by cation exchange. In the case of $CaCO_3$, Me^{2+} removal takes place via (3) ion exchange, followed by (4) a slower recrystallization process that transforms the metal carbonates ($MeCO_3$) into metal dioxides (MeO_2).

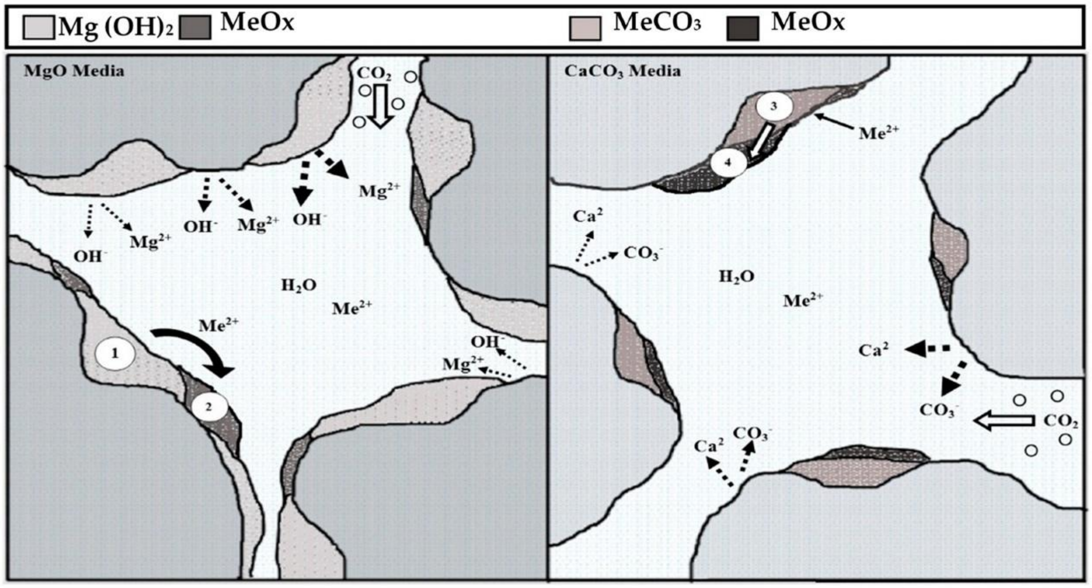

Figure 2.6. Mineralisation process of MgO and $CaCO_3$ in soft water with dissolved divalent metals; the thickness of the dashed arrows in the diagram indicates the relative rate of the reactions. Reproduced from Szymoniak et al., 2022 [95][f]

Higher mineral content in water is generally associated with higher pH values, including higher alkalinity and hardness. Soft and corrosive waters typically have low pH and alkalinity. MgO when dissolved in water regulates the pH of the effluent. The release of OH^- by $Mg(OH)_2$ is slow due to its low solubility in water [96]. After a rapid increase in pH with MgO dissolution, the pH stabilizes and remains in the range of $8 - 10$, providing long-term alkalinity [97]. This alkalinity is primarily a result of the enhanced dissolution process, facilitated by the intentional addition of CO_2 sources. MgO removes twice the amount of acidity compared to a traditional limestone contactor [98]. However, the exclusive use of MgO can result in overcorrection of the pH, so it is recommended as a complement to the calcite contactor, producing mineralized water rich in Ca^{2+} and Mg^{2+}.

The performance of MgO treatment systems may decrease due to the reduction of medium permeability by passivation, even when a minimal amount of the reagent is consumed [98]. Operational lifetime is improved by mixing MgO with an inert material, such as wood chips or quartz sand, which increases reactivity and slows passivation while keeping the permeability of the system high [99]. In water treatment, the parameters affecting the dissolution of MgO and $CaCO_3$ are similar, allowing their dissolution to be optimized without interfering with each other. However, both media have different dissolution responses, especially in terms of Ca^{2+} and Mg^{2+} concentrations, which impacts remineralization in a combined contactor of both minerals [100].

2.8 Cost of water conditioning

Factor like effluent quality, selected technology, and the cost of consumables influence the cost of post-treatment conditioning (**Table 2.4**). Typically, mineralisation processes based on calcium, such as limestone dissolution and lime/carbon dioxide, are considered.

Shemer et al., 2015 [56] states that in 2013 was developed an optimization model for mineralisation with lime/carbon dioxide, it included the blending of remineralized water with untreated

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[f] Reproduced from: Szymoniak, L., Claveau-Mallet, D., Haddad, M., & Barbeau, B. (2022). Application of Magnesium Oxide Media for Remineralization and Removal of Divalent Metals in Drinking Water Treatment: A Review. Water, 14(4), 633.https://doi.org/10.3390/w14040633. ©The Authors, some rights reserved; exclusive licensee MDPI. Distributed under a Creative Commons Attribution NonCommercial License 4.0 (CC BY-NC) http://creativecommons.org/licenses/by-nc/4.0/

demineralized water. The model estimated an optimal total cost of 4.6 US ¢/m³ for a plant with six calcite contactors, a permeate flow rate of 43,000 m³/day, and a final product water quality of 80 mg CaCO3/L.

In 2011, Voutchkov [101] mentioned that dosing magnesium using sulfate salts or magnesium chloride increased the amortized capital cost by 0.1 US ¢/m³ and operational costs by 1.7 US ¢/m³ for a feed of 10 mg/L of Mg^{2+}. Table 5 summarizes the cost range for common calcium-based remineralization processes and proposed magnesium-based post-treatment methods.

Table 2.4. Total costs of remineralization processes based on calcium and proposed magnesium-based methods [56]

Remineralization Method	**Parameter Added**	**Cost (US ¢/m³)**	**Source**
$Ca(OH)_2 + CO_2$	Alkalinity, Ca	5.8–8.8	Shemer et al., 2015
Optimized $Ca(OH)_2 + CO_2$	Alkalinity, Ca	4.6	
Limestone + CO_2	Alkalinity, Ca	4.3–9.9	
Limestone + H_2SO_4	Alkalinity, Ca	2.2–5.2	
Limestone + Mg salts	Alkalinity, Ca, Mg	Limestone cost + 1.7	
Dolomite + H_2SO_4	Alkalinity, Ca, Mg	5.2–10.6	
Mg salts (e.g., $MgCl_2$)	Mg	1.7	Voutchkov, 2011

Documentation on the costs of MgO or mixed $CaCO_3$/MgO mineralization is limited. Dosing Mg^{2+} using $MgSO_4$ or $MgCl_2$ is not considered economically viable or technically feasible, as the goal is to create a cost-effective, low-maintenance treatment system in the residential level. In contrast, MgO media present an opportunity to simplify the treatment process by simultaneously offering remineralization and metal removal benefits. This could be particularly advantageous in remote communities under survival conditions.

In 2021, MgO media certified to NSF/ANSI Standard 60 was priced in US at \$5.73 per kilogram, or approximately \$20,530.40 per cubic metre, making it more expensive than calcite (\$12,028.40/m³) and dolomite (\$15,333.00/m³). However, the suppliers typically recommend adding a maximum of 20% of MgO to prevent overcorrection of pH, which increases the material cost when integrated into treatment system designs [95].

2.9 Natural Materials as Mineralizing Agents

In the context of remote communities facing survival conditions, traditional consumables used in treatment systems are not always viable options due to the associated maintenance and operational costs that may not be feasible in these settings. Access to water remains a significant challenge for these communities, with limited resources and water quality compromised to the point where it may not be safe for consumption. Inspiration for a viable solution came from examining local mineral compounds in the environment of these communities, leading to the idea of a mineralization system that could be deployed in atmospheric water generation systems. Potential materials considered for this process include natural substances like soil, clay, and various sediments such as sand and gravel.

2.9.1 Standard Classification of Soils

The Canadian soil classification system has been developed over the past 80 years, during which the very definition of soil has evolved [102]. Today, soil is regarded as a continuous material that varies according to landform properties, climatic factors, biological activity, and the presence of interacting water bodies. In its broader definition, soil is understood to include mineral particles such as clays, silt, and sediments like sand as part of its physical composition [103]

However, this definition remains limited, as soil cover a wide range of characteristics including color, rock fragments or stoniness, consistency, porosity, clay films, ice, roots, and ultimately, soil texture [104]. The latter is described in detail in **Table 2.5**, where particle diameter is used to associate specific terminology that facilitates a more accurate identification of soil types from its primary particles.

Table 2.5. Particle Size-Based Soil Classification Using the Canadian System [104]

Material Type	Particle Size (µm)
Boulder / Stoney (rounded or angular)	> 250,000
Cobbles or Gravelly (rounded) / Angular cobbly or gravelly / Cherty	80,000 – 250,000
Very coarse sand	2,000 – 1,000
Coarse sand	1,000 – 500
Medium sand	500 – 250
Fine sand	250 – 100
Very fine sand	100 – 50
Silt	50 – 2
Clay	≤ 2
Fine clay	≤ 0.2

Historically, soil maps have played a critical role in advancing soil classification efforts, offering valuable insights into soil-forming factors and the geographic distribution of soil types [105]. However, it is important to acknowledge that global knowledge of soil properties remains far from complete, which continues to limit the development of a fully standardized international classification system [104]. The Canadian soil classification system includes the soil texture triangle as a tool that contributes to the standardization process by enabling classification based on the proportions of clay, silt, and sand present in the soil matrix (**Figure 2.7**).

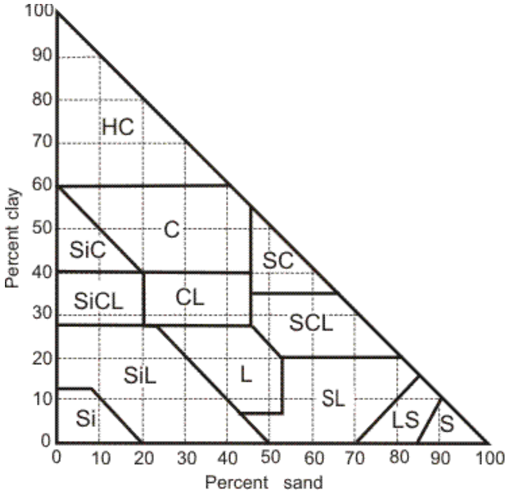

Figure 2.7. Soil texture triangle as a classification tool, where the abbreviations are commonly used: S for sand, LS for loamy sand, SL for sandy loam, and SCL for sandy clay loam. CL refers to clay loam, L to loam, and SiL to silt loam. For finer textures, Si means silt, SC is sandy clay, SiCL is silty clay loam, SiC is silty clay, C is clay, and HC stands for heavy clay. Reproduced from Agriculture and Agri-Food Canada, 1998 [104][g]

2.9.2 Soil

Soil is a shallow layer of the earth's crust composed of a mixture of mineral and organic matter. It functions as a dynamic ecosystem, maintaining diverse organisms and serve as a fundamental component in food production. Its formation is influenced by anthropogenic and geogenic factors [106,107]. The type of rock found beneath the soil is the main factor determining its chemical composition. Over time, minerals break down through weathering, a natural geological process caused by physical forces such as temperature changes or water flow. Nearby mineral deposits can also influence the soil chemical composition, allowing it to absorb small amounts of elements that may be transported by wind, water, or living organisms. All of the this leads to variations in its mineral composition [108].

The degree of decomposition of soil minerals through weathering determines the number of ions released into the surrounding solution, which directly affects the solution's composition (**Figure 2.8**). Each mineral has a specific solubility, and the equilibrium is influenced by the interactions of

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[g] Soil Classification Working Group. (1998). The Canadian system of soil classification (3rd ed.). Agriculture and Agri-Food Canada; National Research Council Canada. Reproduced with permission from Agriculture and Agri-Food Canada (AAFC) through the Government of Canada's Open Government Licence – Canada (OGL–Canada).

multiple solid phases. Minerals formed at high pressure and temperature can either dissolve or transform into more stable forms at the Earth's surface; therefore, solubility varies significantly; for example, sodium salts dissolve readily, while compounds containing Cr, Al, and Fe are much less soluble. In fact, weathering occurs because the products have lower free energy than the original minerals. If a mineral dissolves, the reactions can be represented by an equilibrium equation with a known constant [109].

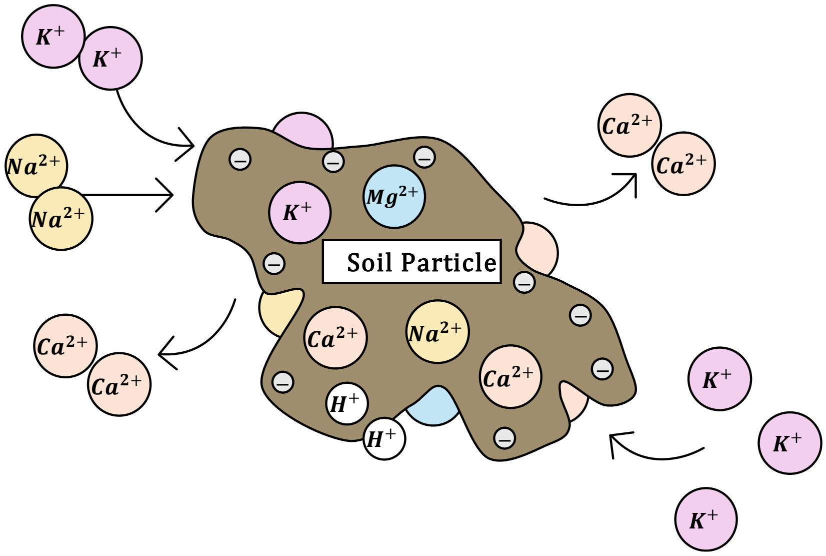

Figure 2.8. Ion exchange capacity of soils. Inspired from Plant physiology [110]

As stated by Novozamsky & Beek, 1976 [111], the presence of CO_2 gas in soil systems limits the maximum concentration of cations in the soil solution, particularly Ca^{2+}, which forms low-solubility carbonates. Soils often contain crystalline calcium carbonates such as calcite and aragonite, with the latter being metastable relative to calcite. Other carbonates, including dolomite ($CaMg(CO_3)_2$), magnesite ($MgCO_3$), and siderite ($FeCO_3$), are also present in certain soils, especially under anaerobic conditions. The solubility constants for these minerals are found in the literature or can be calculated using thermodynamic data. Local CO_2 pressure and pH control the maximum concentration of relevant cations, and the presence of solid-phase carbonates stabilizes their concentrations in the soil solution. Under leaching conditions, soils containing $CaCO_3$ become nearly saturated with Ca^{2+} ions, which impacts the soil's physical properties, such as structural stability and hydraulic conductivity.

McBride, 1989 pointed out that knowing the elemental composition of soil is often insufficient for evaluating the availability of elements to plants. For example, despite high levels of Fe and Mn in many soils, plants often suffer deficiencies of these elements. Consequently, soil analysis has shifted towards measuring extractable fractions of elements, offering a more accurate assessment of element availability. However, these analyses remain empirical and do not provide a detailed understanding of the chemical forms of metals in the soil [112].

The solubility of soil ions is primarily regulated by the most soluble minerals available. Over time, soil formation processes progressively remove these highly soluble minerals, leaving behind the most stable ones, which ultimately dictate ion availability at lower concentrations. The abundance of silicate minerals in soils also results in strong interactions between silica and various ions.

Soil chemistry traditionally focuses on key factors like pH, organic load and cation exchange capacity (CEC). The CEC is a fundamental concept in soil chemistry, it refers to the ability of soil, especially clay, to absorb and retain positively charged ions or cations, such as sodium, magnesium and calcium, which are essential for soil fertility. While cations are critical for nutrient uptake, anions like nitrate and sulfate also play a role in soil chemistry. Generally, soils are negatively charged, and the more negative the soil, the higher its cation exchange capacity.

Water’s chemical properties significantly affect its behavior in soils, interacting with organisms, mineral surfaces, and air spaces. Owen W. Duckworth et al., 2014 [113] relied on studies by Eisenberg & Kauzmann 1969, Hasted 1972, Burgess 1978, Essington 2004, Franks 2000 to show that at 20°C, the water’s high dielectric constant is equal to 80.1, this is due to its dipole moment and nonlinear structure. This makes water an excellent solvent, allowing it to dissolve ionic solids by surrounding them with solvation spheres (**Figure 2.9**). By stabilising anions and cations, water reduces their tendency to associate, increasing solubility and facilitating chemical interactions in the soil environment.

Water’s ability to dissolve ionic substances is vital in soil systems, where it dissolves minerals and facilitates nutrient uptake. Pauling,1988, as cited in Duckworth et al., 2014 [113] stated that water’s high dielectric constant breaks the attractive forces between oppositely charged ions, allowing them to dissolve and interact more freely. This solvation process is essential in soil chemistry, as it influences nutrient availability, mineral weathering, and overall soil health, demonstrating the crucial role of water in soil dynamics and environmental processes.

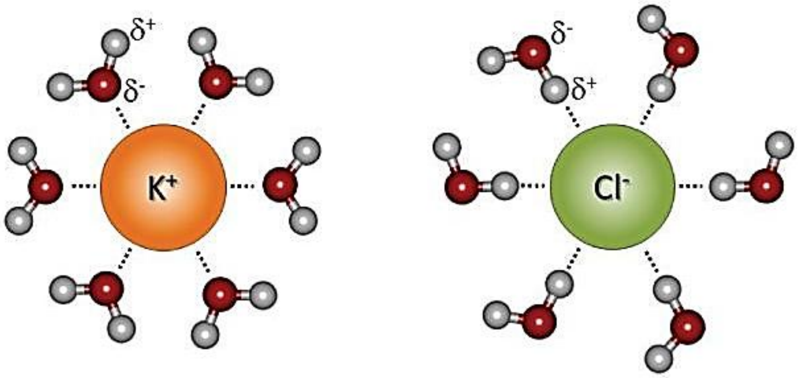

Figure 2.9. Solvation spheres. Reproduced from Owen W. Duckworth et al., 2014 [113][h]

Havlin et al., 2005, as cited in Duckworth et al., 2014 [113] states that potassium chloride (KCl), a widely used potassium source in fertilizers, dissolves when it comes into contact with water, following this process shown in **Equation 2.17**:

$$KCl_{(s)} + (m+n)H_2O_{(l)} \leftrightarrow [K(H_2O)_m]_{(aq)}{}^{+} + [Cl(H_2O)_n]_{(aq)}{}^{-} \qquad \mathbf{(2.17)}$$

Where, m and n represent the number of water molecules in each solvation sphere. The number of water molecules in the solvation spheres are influenced by factors such as the ion size, chemical properties, ion charge, and concentration of the ions in solution (Burgess, 1978, as cited in Duckworth et al., 2014) [113].

Ionic potential, which represents to the total sum of all dissolved ions and inherently limits dissolution, is also an important factor. For example, while KCl dissolves easily due to its high solubility, other minerals in soil behave differently, as their solubility and tendency to precipitate depend on their specific characteristics and the surrounding solution chemistry. Water's capacity to either enhance dissolution or prevent precipitation is crucial in various soil processes, affecting fertility, salinity, and mineral weathering (Essington, 2004; Brantley, 2008; Havlin et al., 2005 as cited in Duckworth et al., 2014) [113].

It is stated that one of the key properties of water is its ability to function as an acid and a base, a characteristic known as amphoterism (IUPAC, 1997 as cited in Duckworth et al., 2014) [113]. The polar nature of the water makes it highly susceptible to ionic dissociation, resulting in the formation

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[h] From: Duckworth, O. W., Heitman, J. L. & Polizzotto, M. L. (2014) Soil Water: From Molecular Structure to Behavior. *Nature Education Knowledge* 5(8):1. Reproduced with permission from Nature Education content.

of hydroxide ions and protons. (Eisenberg & Kauzmann, 1969; Pauling, 1988 as cited in Duckworth et al., 2014) [113]. The **Equation 2.18** presents the amphoteric characteristic of water.

$$H_2O_{(l)} \leftrightarrow H_{(aq)}{}^{+} + OH_{(aq)}{}^{-} \qquad \mathbf{(2.18)}$$

The amphoteric nature of water is critical to acid-base chemistry, directly influencing soil pH. Soil pH, often referred to as the "master variable," significantly impacts plant growth, environmental quality, and soil formation (Sparks, 2003, as cited in Duckworth et al., 2014) [113].

Soil pH plays a critical role in determining the availability of minerals, which can influence their potential release during water remineralization processes. Soil with pH values between 6.5 and 8.0 are considered favorable for the solubility of a broad range of essential ions. Outside this range, the solubility of certain minerals may decrease, limiting their contribution to water mineralization. Additionally, under acidic conditions, the increased solubility of ions like aluminum, manganese, and iron, often present in soils, may lead to their leaching, which can affect the safety and quality of the treated water. Understanding how soil pH influences mineral availability is therefore key to evaluating the suitability of natural materials for use in low-consumable remineralization systems.

On the other hand, alkaline soils can cause an overabundance of calcium, which can react with nutrients such as phosphate, thus reducing their availability. This interaction further hampers nutrient uptake. Understanding pH ranges and their impact on nutrient availability is crucial for effective soil management, as shown in the general nutrient availability ranges for mineral and organic soils in **Figure 2.10**

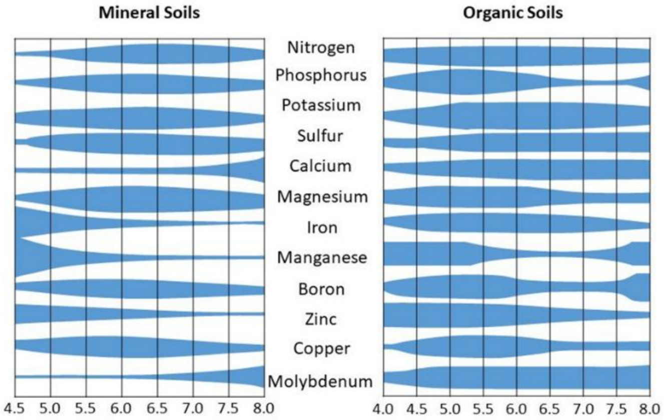

Figure 2.10. Effect of Soil pH on Nutrient Availability in Mineral and Organic Soils. Reproduced from Canadian Society of Soil Science, 2021 [114] [i]

The average soil pH across North America is 6.4, with 27% of tested samples falling below 6. A pH of 6.0 or higher is generally preferred pH for remineralization. Regions in the southeastern United States (US) tend to have the lowest median pH values, while levels generally increase moving westward (**Figure 2.11**). In areas where the median pH is slightly above but near 6, a significant portion of soil tests indicate acidity levels that may warrant careful consideration of lime applications.

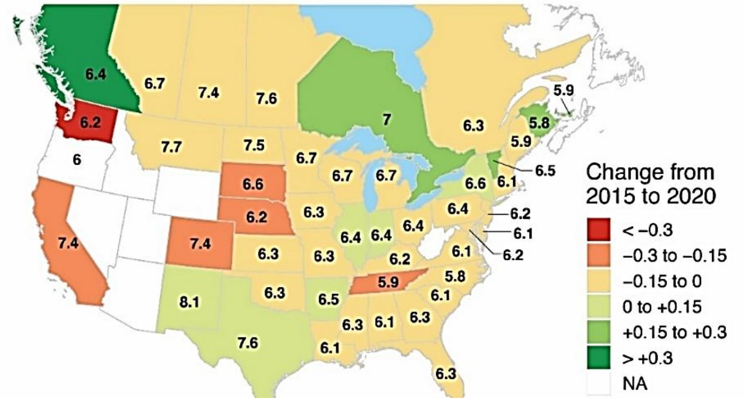

Figure 2.11. Median Soil pH in 2010 and Changes Since 2005 for States and Provinces with ≥2,000 Tests. Reproduced from Soil Test Summary (Soil Test Summary, 2020). [j]

2.9.3 Clay

Clay is a term that refers both to a specific grain size and a group of minerals. These naturally occurring phyllosilicates originate primarily from the weathering of rock minerals, forming layered structures that give clay its unique plasticity. This property allows it to harden when dried or exposed to heat. The mineral composition of clay greatly influences its plasticity, with certain minerals, such as smectites, demonstrating significant reactivity even in small amounts [117]. Plasticity in clay minerals follows a general pattern, where sodium montmorillonite exhibits the

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[i] Reproduced from: Canadian Society of Soil Science. Digging into Canadian Soils. 2021. ©The Authors, some rights reserved; exclusive licensee Canadien Society of Soil Science. Distributed under a Creative Commons Attribution NonCommercial License 4.0 (CC BY-NC) http://creativecommons.org/licenses/by-nc/4.0/

[j] From: The Fertilizer Institute. Median and Change in Median Soil Test Levels 2020. https://soiltest.tfi.org/maps/Median (accessed March 17, 2025). Reproduced with permission from The Fertilizer Institute.

highest plasticity, followed by calcium montmorillonite, sepiolite, attapulgite, illite, and, lastly, kaolinite and halloysite, which have the lowest plasticity (White, 1949; Bain, 1971, as cited in Moreno-Maroto & Alonso-Azcárate, 2018 [117])

Clay particles are highly versatile in their ability to interact with various cations and anions, playing a crucial role in soil and environmental chemistry. These materials can absorb and retain ions in an exchangeable form, which is essential for their behavior in soil systems. The interaction between clays and ions enables them to act as ion exchangers, helping to regulate the availability of nutrients and other chemicals in the soil.

The ability of clays to exchange ions in an aqueous solution enhances their role in soil fertility and pollutant removal processes. In particular, the exchange of cations and anions in clay materials is fundamental to understanding their behavior in natural systems and their use in industrial applications (**Figure 2.12**).

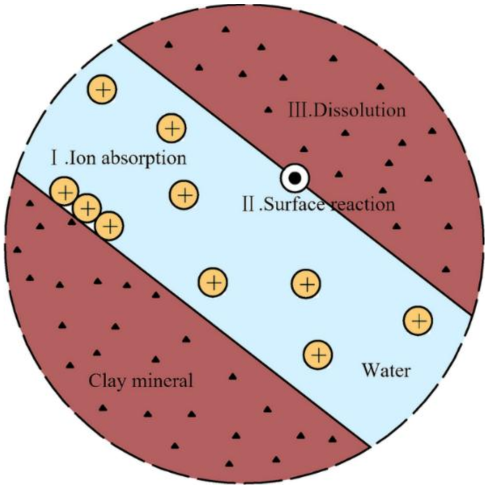

Figure 2.12. Diagram of ion diffusion and clay dissolution at water–mineral interface. Reproduced from Liu et al., 2023 [118][k]

Gaboreau et al., 2020 [119] building on studies by Oelkers et al., 1994 ; Devidal et al., 1997; Lasaga, 1998; Cama et al., 2000 ; Marty et al., 2011, stated that clay minerals dissolve slowly. Typically, experiments on clay dissolution evaluate clay solubility by monitoring the release of

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[k] Reproduced from: Liu, Z., Liao, J., Xia, C. *et al.* Micro-meso-macroscale correlation mechanism of red-bed soft rocks failure within static water based on energy analysis. *Acta Geotech.* 18, 6457–6474 (2023). https://doi.org/10.1007/s11440-023-01893-6. ©The Authors, some rights reserved; exclusive licensee Springer Nature. Distributed under a Creative Commons Attribution NonCommercial License 4.0 (CC BY-NC) http://creativecommons.org/licenses/by-nc/4.0/

elements as the mineral reaches equilibrium in a solution over the time. These experiments are carried out over long periods. For example, in a 7 year study, vermiculite showed a shift in exchangeable cations from 96% Ca and 4% Mg initially to 88% Ca and 11% Mg, indicating magnesium adsorption. Smectite exhibited rapid leaching of cations like Ca and K, while illite, a clay particle with a layered structure, showed a general leaching of elements like Fe, Mg, and Al over time [119]

Montmorillonite clays can have their base components extracted by treatment with 6 N hydrochloric acid for several hours. When immersed in deionized water, these clays dissolve to a concentration of at least 36 parts per million, even after multiple digestions. For Polkville bentonite, a high-purity montmorillonite, the amount of base components dissolved in deionized water is very low, with values reported at 0.0236 grams per liter for the first water-material contact and 0.0102 grams per liter for the second contact of the same sample [120]. Another study observed that Na and K water concentrations decreased exponentially with time, with a significant reduction during the first month of saturation. In contrast, Ca and Mg concentrations showed little change. The transport of Na and K into the rock caused a decrease in pH in the aqueous solution, highlighting the different behaviors of the different clay types in releasing ions into solution [118].

2.9.4 Sediments

Sand and gravel, despite being classified as sediments, share this classification because they originate from the erosion and sedimentation of rocks as part of the Earth's natural geological processes.

Sand and gravel deposits often consist of minerals and rocks that are resistant to weathering. Sands are mainly composed of quartz, which forms from the breakdown of quartz-bearing rocks, while gravels typically contain granite, gneiss, quartzite, sandstone, or limestone. Sandy soils are characterized by a low nutrient retention capacity, which results in macronutrient leaching. The polarity of charges on sand particles is size-dependent, with larger particles carrying positive charges and smaller ones carrying negative charges (Rudge, 1913; R. Greeley, R. Leach, 1978; Zheng et al.,2003; as cited in Xie et al., 2020) [121]

The particle size of sand follows a bell curve, with an average diameter of 203 μm and a variance of 60. Particles larger than 225 μm carry a positive charge, whereas negatively charged particles are for those smaller than 175 µm. This indicates that finer particles contribute significantly to the sand's ion exchange capacity, which is crucial for its function in environmental processes, including nutrient exchange and filtration (**Figure 2.13**).

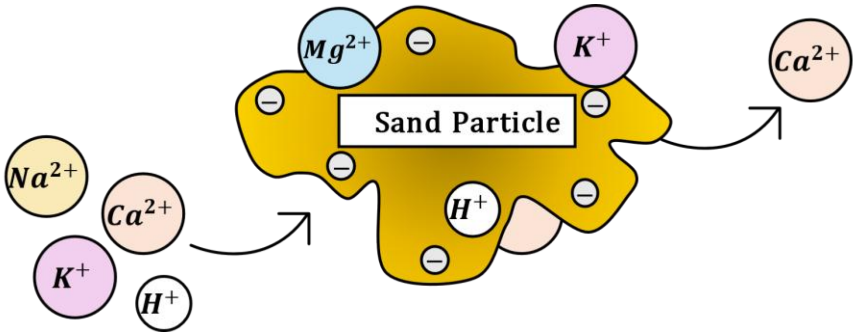

Figure 2.13. Schematic look at cation exchange in a sand particle. Inspired from TurfCare,2019 [122]

A study on the adsorption of seawater ions by sand highlights that seawater is a complex solution containing metal ions such as sodium, potassium, magnesium, and calcium, along with anions like sulfate, chloride, and carbonate. The percolation of seawater through sand affects its chemical and physical properties, particularly the calcium and magnesium ions, which are in a delicate equilibrium. A slight pH change can cause their precipitation (Atkins 1919, as cited in Stowell, 1927 [123]). This demonstrates the significant role of sand in regulating the concentrations of key ions in natural water systems. The research concluded that ions in seawater are typically adsorbed by sand, and the percolation process leads to slight anomalies in calcium and magnesium ion concentrations. Sand is not an inert adsorbent; it can exchange calcium ions for magnesium and sodium. However, this ion exchange and adsorption process is insufficient to cause significant changes in pH or to induce hydrolysis, as long as the volume of seawater is large enough. [123].

The main difference between gravel and sand lies in their size. Gravel consists of rock fragments ranging from granular particles to pebbles, often mixed in a matrix of clay and sand. The structure of gravel varies considerably, sometimes presenting a wide range of particle sizes or, in other cases, a single size distribution [124].

A study indicated that most pebbles within a gravel matrix can range in diameter from approximately 0.25 mm to 6.35 mm, or even from 76.2 mm to 152.4 mm. Meanwhile, in associated granular gravel, particle sizes can decrease progressively, from the largest fragments down to sand-sized grains as small as 25.4 µm. Gravel is thought to be formed by typical selective deposition and transport processes, influenced by local changes in water velocity and turbulence in fast-flowing streams[125] .

Both sand and gravel hold commercial value in construction due to their role in operations like ready-mix concrete, asphalt production, and other aggregate applications [126].

From the author's knowledge, no studies specifically examine water mineralization resulting from gravel or interactions between them. However, an initial clue could be that this material has a lower moisture retention capacity and a lack of mineral nutrients, without finer soil particles to improve water and nutrient retention, coarse soils such as gravel are often ineffective for plant growing [127].

CHAPTER 3 PROJECT OBJECTIVES AND METHODOLOGICAL ASPECTS

3.1 Specific Objectives

The main objective of the project is to develop a low consumable mineralisation system using locally available resources to provide a basic quality of atmospheric water harvested from sorbent-based technologies, enabling drinkability in resource limited communities under survival conditions. While this work focuses on the conditioning of water, microbiological safety aspects are recognised but remain outside the scope of this study.

The specific objectives of this project are based on the following points:

- Determine the target levels for water mineralization, based on scientific and government specifications.
- Identify and test various widely-available native resources for their ability to deliver mineral content at or near target levels.
- Assess the water quality parameters for the candidate resources capable of providing sufficient mineral levels.

This study began with a review of the state of the art in post-treatment processes for AWH water, focusing on the lack of minerals in AWH water, which is similar to deionized water. Given the WHO's recommendations on mineral intake through drinking water, the review explored strategies for water remineralization, including approaches used for reverse osmosis (RO) water. Documented methods include direct dosing, blending with hard water, and mineral dissolution using materials like Corosex™ and Calcite. While effective, these consumable-based methods are not well suited for decentralized systems in low-resource settings. As an alternative, this work proposes using native materials (soil, clay, sediments) with natural mineral content and ion exchange capacity. The study explores their leaching potential, compares them to manufactured options, and evaluates their ability to improve water quality post-contact. **Figure 3.1** addresses the experimental process used to meet the specific objectives previously discussed.

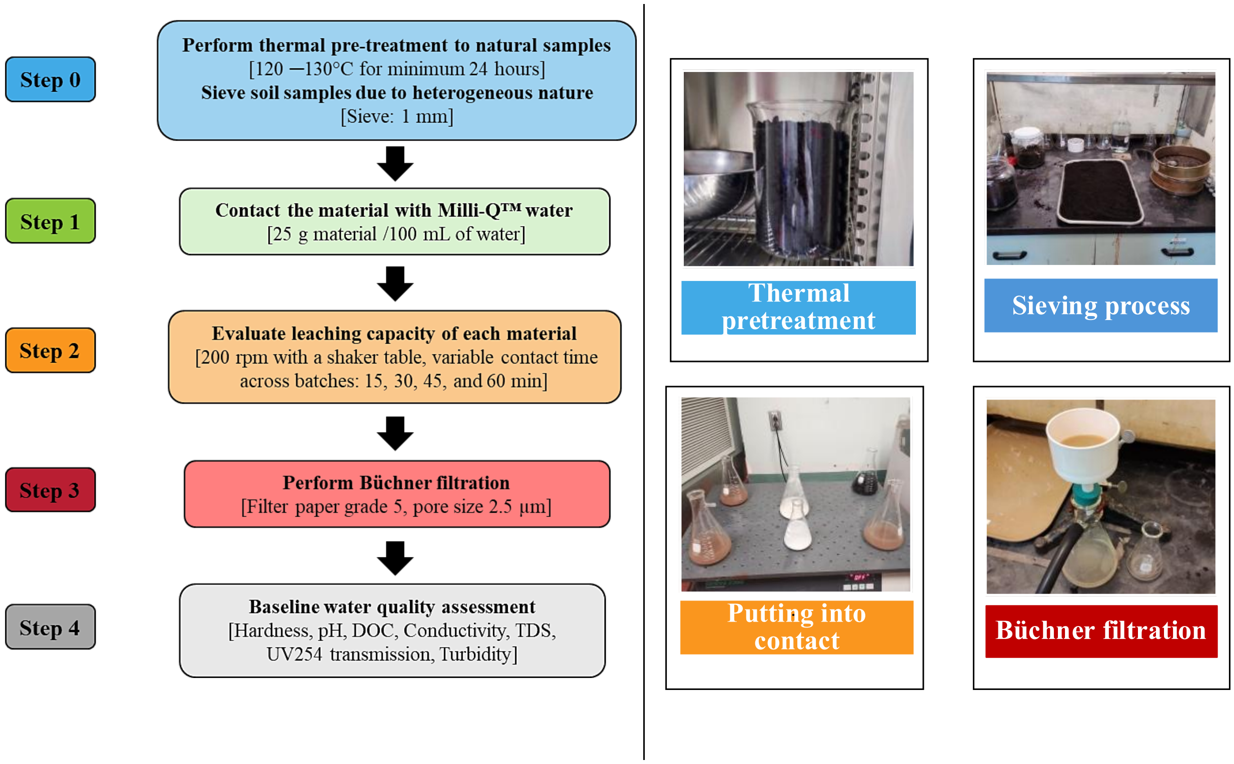

Figure 3.1. The experimental process implemented (on the left). The images provide an overview of the pretreatment, contact, and filtration processes.

3.2 Laboratory prototype for Atmospheric Water Harvesting

The laboratory-scale AWH water prototype runs eight cycles per day, producing approximately 30 mL of water per cycle, resulting in a total daily yield of around 240 mL (**Figure 3.2**). The system operates by allowing the entry of saturated air from a humidifier. Fans drive this humid air toward the sorbent materials, which capture water through capillary action and chemical affinity for water molecules. Once the sorbents are saturated, desorption is triggered when the internal relative humidity reaches a value around 60%. The system heats up to nearly 80°C, releasing the water as vapor. This vapor is then collected through a distillation column process. All operations such as: gate control, fan activation, temperature regulation, are managed via LabVIEW 2023 Q3 software.

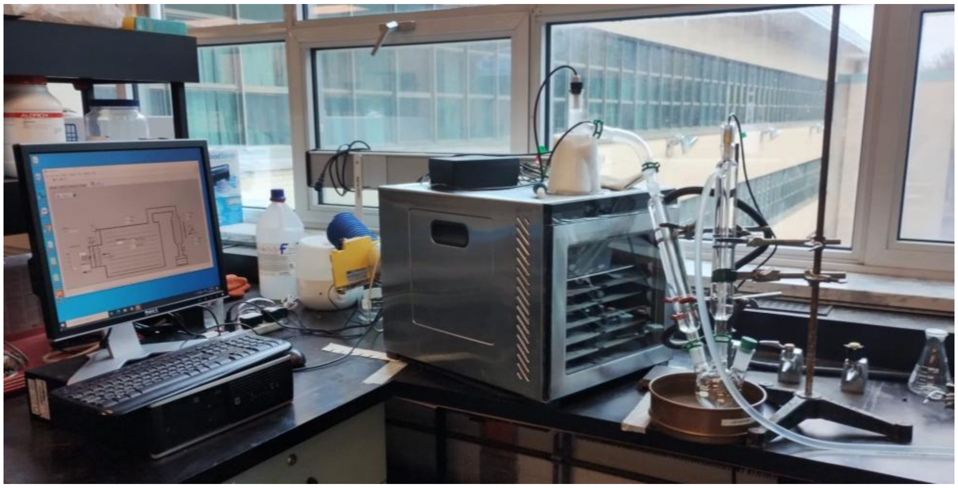

Figure 3.2. First generation atmospheric water harvesting laboratory prototype

3.3 Basic water quality assessment

Following the Büchner-type filtration (Step 4*,* **Figure 3.1**), a preliminary assessment of the water quality was carried out after contact with the various materials. The objective was to compare the measured parameters with those suggested in the literature for drinking water standards. Water quality was assessed using protocols described in *Standard methods for the examination of water and wastewater* [47]

3.3.1 Turbidity – Method 2130

Turbidity is related to water clarity and serves as a measure of the suspended solids and colloids present in the water (**Figure 3.3**). It is typically reported in nephelometric turbidity units (NTU). The measurement is carried out using a laboratory instrument called nephelometers (Hach TL2300), in which a sample is illuminated by an incident beam of light. The path of the scattered light is measured at 90 degrees to the path of the incident light beam illuminating the sample. In essence, turbidity reflects an optical property of water, where particles cause light to scatter and absorb rather than allowing it to transmit freely.

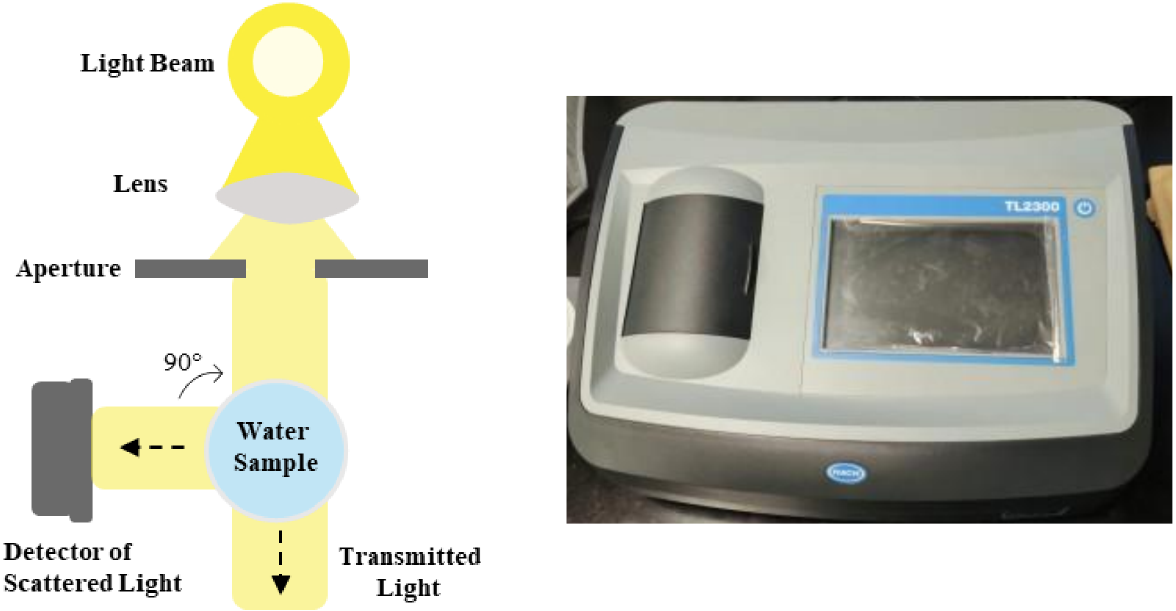

Figure 3.3. Diagram of the principle of turbidity (on the left - inspired from Zakaria et al., 2018 [128]) and a photo of the equipment used.

3.3.2 Conductivity – Method 2510

The ability of an aqueous solution to conduct electricity is a useful parameter for detecting most inorganic compounds and ions, making it an important indicator of water mineralization. Conductivity is typically represented by the letter K and is frequently expressed using micromhos per centimeter (µmho/cm). However, under the International System of Units (SI), it is measured in siemens (S), with milli siemens per meter (mS/m) being the most common format. **Figure 3.4** shows the principle and laboratory equipment used to measure conductivity in water (Mettler Toledo SevenDirect SD30/InLab® 731-ISM probe).

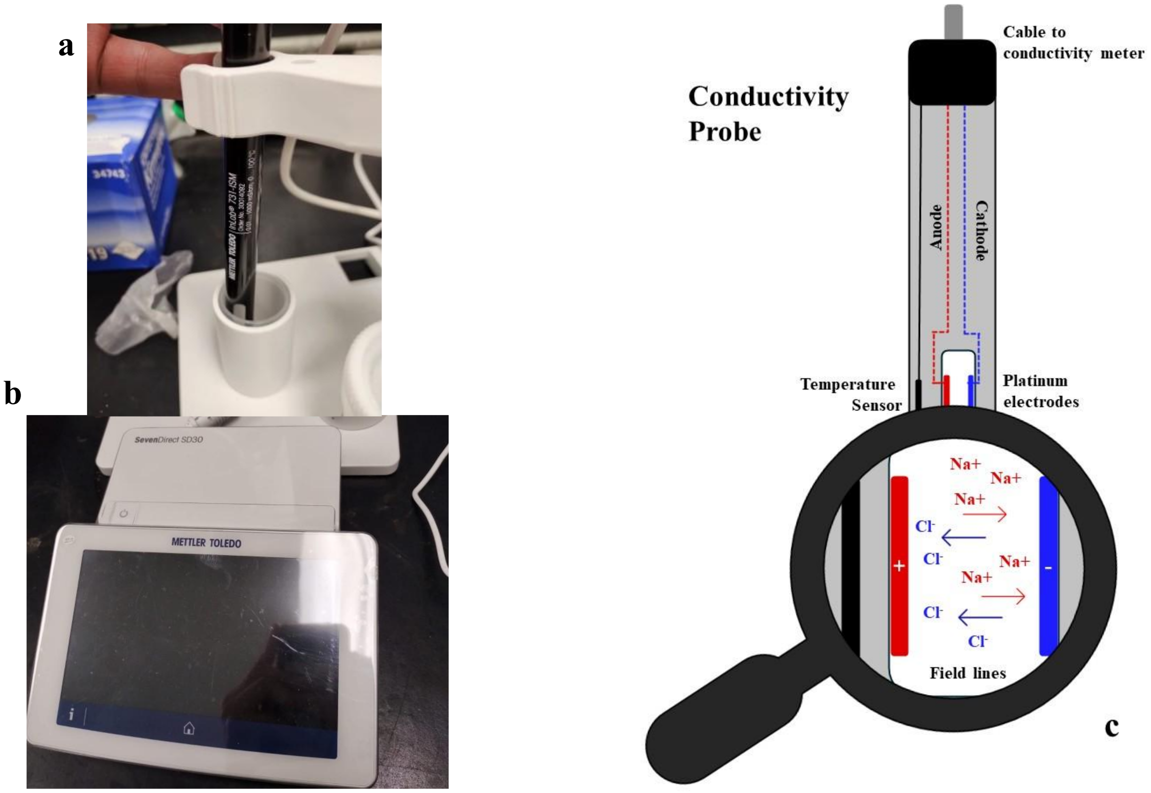

Figure 3.4. Diagram of the principle of conductivity in a probe (on the right - inspired from Connelly, 2017 [129]) and a photo of the probe (a) and the equipment (b) used.

3.3.3 UV 254 nm – Method 5910

A non-specific measurement that helps determine the presence of aromatic compounds can be done in water samples using a spectrophotometer (Ocean Optics USB4000 – XR1 – ES) set to a wavelength of 254 nm at room temperature. This parameter is strongly correlated with color, precursors of trihalomethanes (THMs), and organic content. UV absorption is typically reported in units of cm^{-1} or abs/cm.

3.3.4 pH – Method 4500

In water chemistry, pH is one of the most important tests, since many water treatment processes depend on the activity of hydrogen ions (**Figure 3.5**). The intensity of this activity reflects the water's acidity or basicity. This is measured potentiometrically using a standard hydrogen electrode (AR25 pH Meter). The pH scale ranges from 0 to 14, with a value of 7 being considered neutral at 25°C. Depending on the species in solution, the character of the water can be determined.

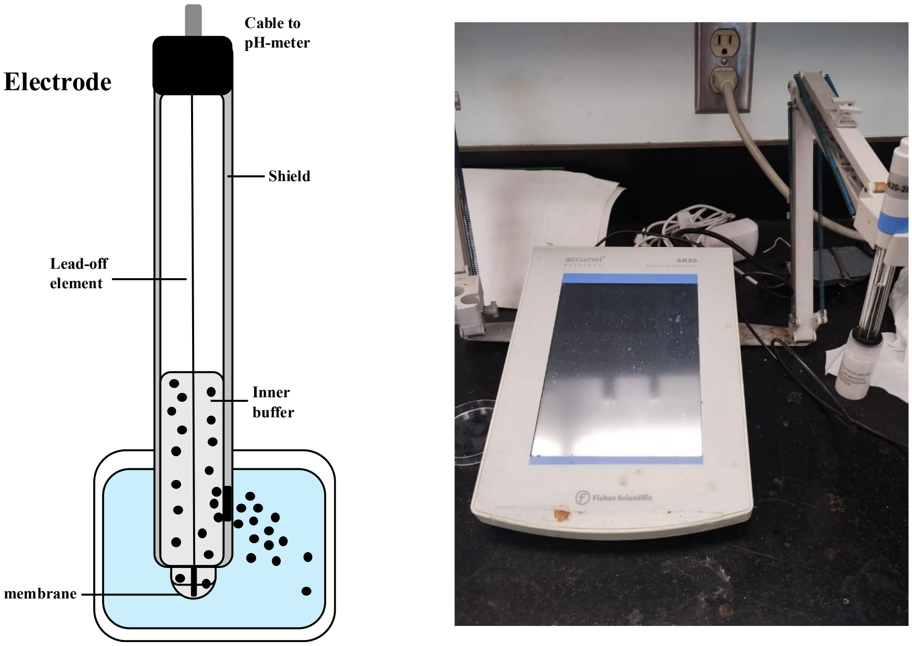

Figure 3.5. Diagram of the principle of conductivity in a probe (on the left - inspired from PharmaSciences, 2025 [130]) and a photo of the equipment used.

3.3.5 Hardness – Method 2340

It is widely agreed that having minerals in drinking water is beneficial, as their optimal concentrations play a key role in determining water quality. To measure ion levels contributing to water hardness, precise identification can be done using atomic absorption spectroscopy with a PerkinElmer Pinnacle 900F, or through ion-specific titrations like Standard Method 3500-Ca. Hardness is then calculated using equations 3.1 or 3.2. As previously discussed, water hardness provides insight into two important ions, calcium and magnesium. which are abundant in water and essential for the body's biological processes. The sum of these ions defines hardness and can be easily measured through complexometric titration using the indicator Eriochrome Black T (EBT), with results typically expressed as milligrams of calcium carbonate per liter. **Figure 3.6** shows the methods used to measure water hardness.

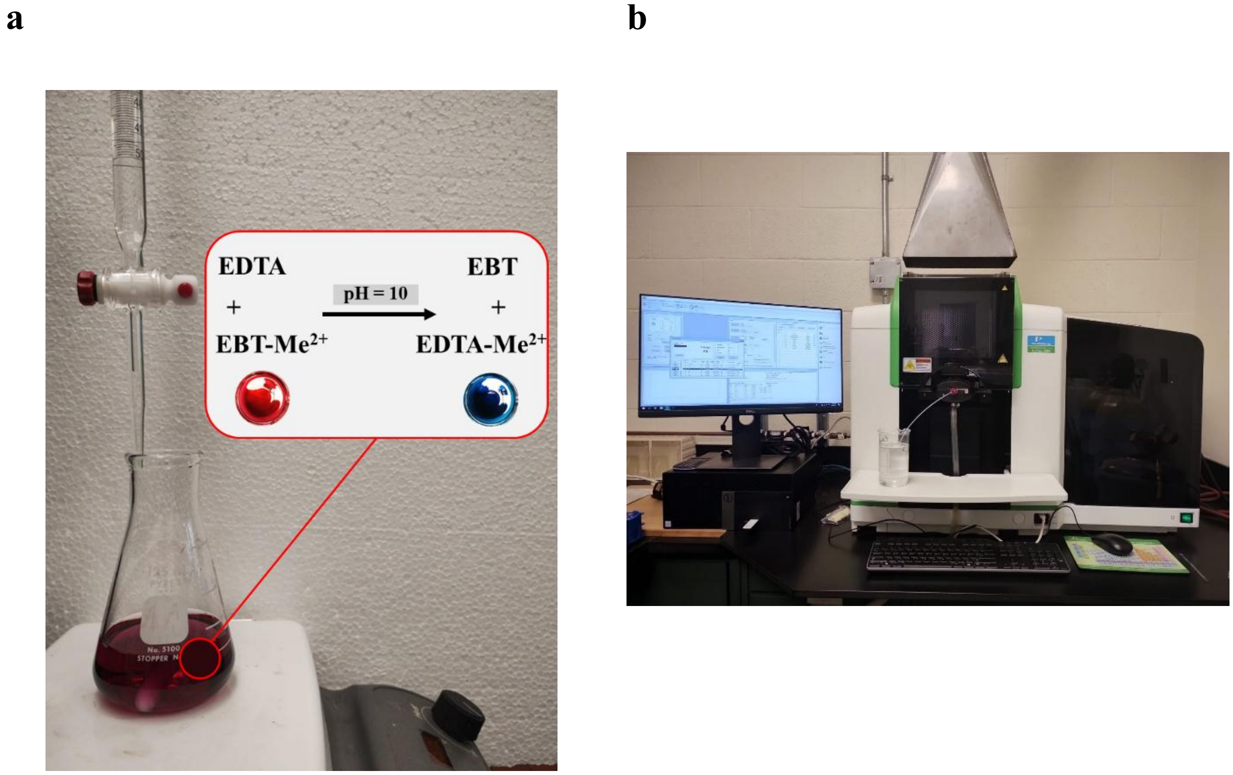

Figure 3.6. Hardness measurement methods used: a) titration set-up with the reaction that occurs between Ethylenediaminetetraacetic acid (EDTA), divalent ions (Me^{2+}) and the indicator EBT; b) Atomic Absorption Spectroscopy equipment.

Hardness calculation

Unless specified otherwise, water hardness is generalized to the total concentration of calcium and magnesium minerals in water, and is calculated using **Equation 3.1**:

$$Equivalent\ CaCO_3 \frac{mg}{L} = \frac{50\ g\ eq^{-1}(CaCO_3)}{20.04\ g\ eq^{-1}\ (Ca^{2+})} \cdot \left[Ca^{2+}, \frac{mg}{L}\right] + \frac{50\ g\ eq^{-1}(CaCO_3)}{12.15\ g\ eq^{-1}\ (Ca^{2+})} \cdot \left[Mg^{2+}, \frac{mg}{L}\right] \qquad (3.1)$$

The equivalent factors are used to convert their concentrations to a $CaCO_3$ basis to facilitate the calculation of total hardness, as shown in the **Equation 3.2**:

$$
\begin{aligned}
Hardness\left(\frac{mg\ CaCO_3}{L}\right) = 2.50 \cdot \left[Ca^{2+}, \frac{mg}{L}\right] + 4.12 \cdot \left[Mg^{2+}, \frac{mg}{L}\right] + \\
1.14 \cdot \left[Sr^{2+}, \frac{mg}{L}\right] + 1.79 \cdot \left[Fe^{2+}, \frac{mg}{L}\right] + \\
1.82 \cdot \left[Mn^{2+}, \frac{mg}{L}\right]
\end{aligned}
\qquad (\mathbf{3.2})
$$

Where Ca^{2+}, Mg^{2+}, Sr^{2+}, Fe^{2+} and Mn^{2+} represent the measured concentrations (mg/L).

3.3.6 Dissolved Organic Carbon (DOC) – Method 5310

Dissolved organic carbon (DOC) is an indicator of the composition of organic compounds dissolved in different oxidation states present in water. This is an important parameter to consider, as it helps identify significant impurities and organic matter that can serve as nutrients for unwanted biological growth (**Figure 3.7**). Additionally, these organic compounds can react with disinfectants, forming byproducts that may pose health risks to humans.

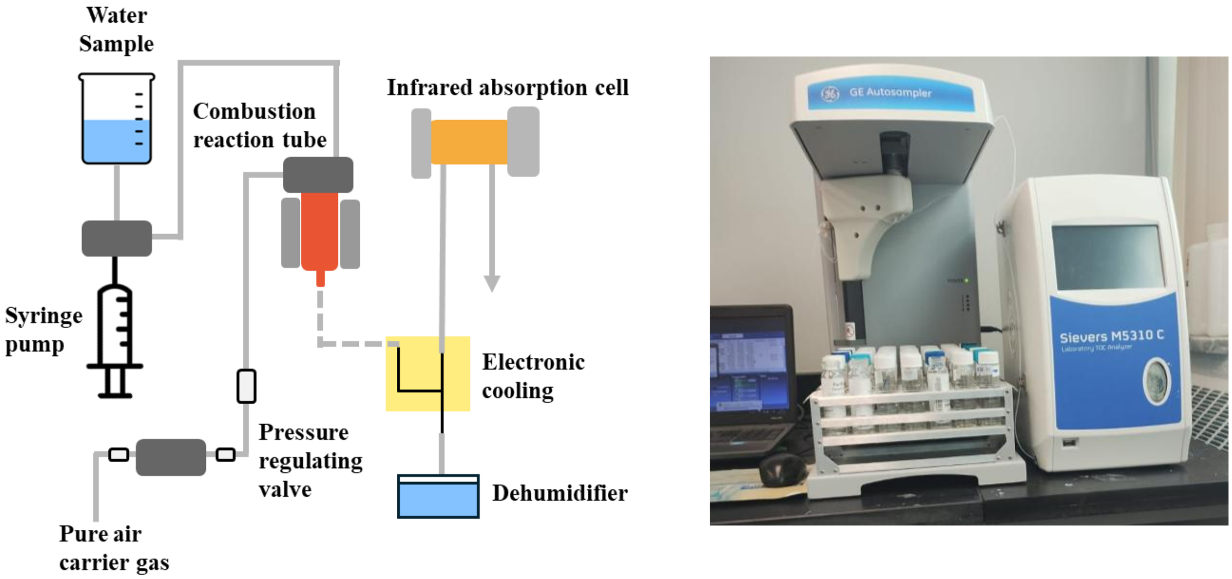

Figure 3.7. Diagram of the measurement of organic carbon in water (on the left - inspired from SHIMADZO, 2025 [131]) and a photo of the equipment used.

Measuring organic content involves converting various organic compounds into a single, measurable substance. The Sievers M5310 C Analyzer oxidize all organic material into CO_2. Once the CO_2 is produced, it is removed from the sample, dried, and then transported by a carrier gas either to a nondispersive infrared analyzer or to a system that measures it through coulometric titration.

3.3.7 Total Dissolved Solids (TDS) – Method 2540

Total Dissolved Solids (TDS) are defined as the fraction of suspended or dissolved solids that can pass through a filter with a pore size ≤ 2 µm. Typically, TDS is measured using a gravimetric method: a pre-weighed, oven-dried dish is used to collect a water sample, which is then heated until complete dryness at a temperature between 103°C and 105°C for a minimum of 24 hours. After drying, the dish is weighed again with the dried solids, and the increase in mass corresponds to the amount of total dissolved solids, usually expressed in mg/L (**Figure 3.8**). This parameter is particularly relevant in drinking water treatment, as it is closely related to palatability, the value of 500 mg/L is the upper threshold for acceptable taste, with higher concentrations potentially triggering adverse consumer physiological reactions.

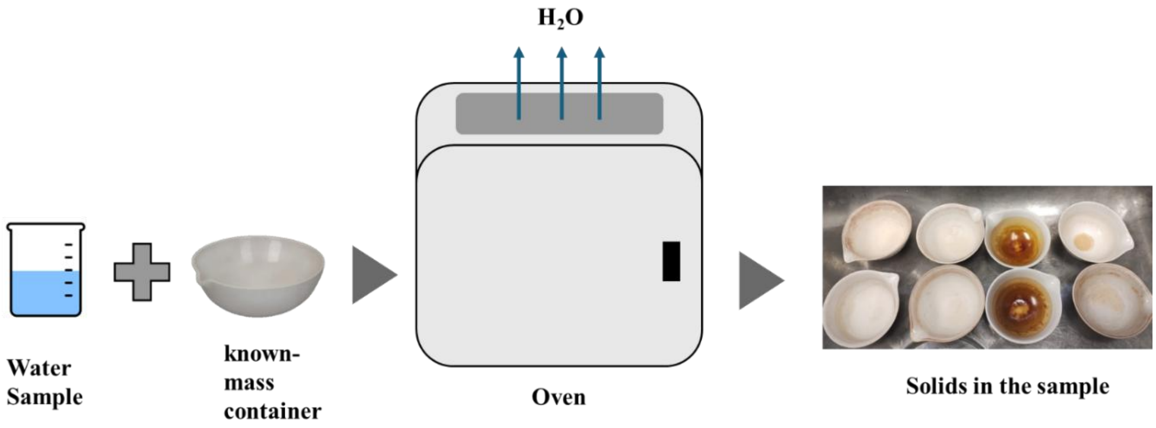

Figure 3.8. Diagram of the principle of total dissolved solids (inspired from CORROSIONPEDIA, 2024 [132])

3.4 Natural materials characterization

3.4.1 Physical characterization

Three morphometric analyses were used to obtain information on surface area, density, and particle size distribution of the natural materials selected as potential mineralizing agents.

The first method consisted of traditional dry sieving, following the procedure described in ASTM C136/C136M [133]. For finer samples, 300 g were analyzed using a series of sieves ranging from 1 mm to 120 µm. For coarser materials, 600 g of clay pebbles and 5 kg of gravel were analyzed using sieves ranging from 2.36 mm to 19 mm. The sample is typically placed at the top of the sieve stack and subjected to mechanical agitation for 5 minutes. The material retained on each sieve was then weighed to calculate the percentage distribution.

As a complementary method, ImageJ software was used to analyze the shape and size of coarse particles from digital images taken with a camera. After image segmentation and thresholding, the equivalent diameter of 81 particles from gravel and clay pebbles, was measured.

The third method, used for fine particles (< 2 µm), involved a Malvern Mastersizer 3000 with Hydro Cell for laser diffraction analysis in water dispersion. This method provided a more accurate and reliable particle size distribution for the fine fraction. The specific surface area was obtained directly from the Mastersizer or calculated from the granulometric analysis obtained, requiring a density value measured using a gas pycnometer (Micromeritics AccuPyc II 1340). All measurements were performed at temperatures between 23.5°C and 24.8°C, using a 10 cm^3 capsule filled completely with each material.

3.4.2 Chemical characterization

The experimental process also includes characterizing the chemical composition of the natural materials used as mineralizing substrates. Identifying the elemental composition of natural materials allows a total ionic balance to be established and compared with the ions released, especially those of interest such as calcium and magnesium. This characterisation also makes it possible to detect the presence of potentially unwanted heavy metals, as the material itself could act as a source of contaminants during the leaching process. It is therefore essential to verify their solubility by analysing the water after contact.

Sample characterization was performed through the detection of elemental composition using an advanced technique based on inductively coupled plasma (ICP) ionization with the support of the external laboratory, Bureau Veritas. In this method (**Figure 3.9**), the sample is introduced into a high-temperature plasma source, where it is atomized and ionized. The resulting ions are then directed into a mass spectrometer, which separates them according to their mass-to-charge ratio. This highly sensitive and precise technique allows for the detection of isotopes and trace elements at concentrations as low as parts per billion (ppb), making it particularly suitable for environmental and water analysis.

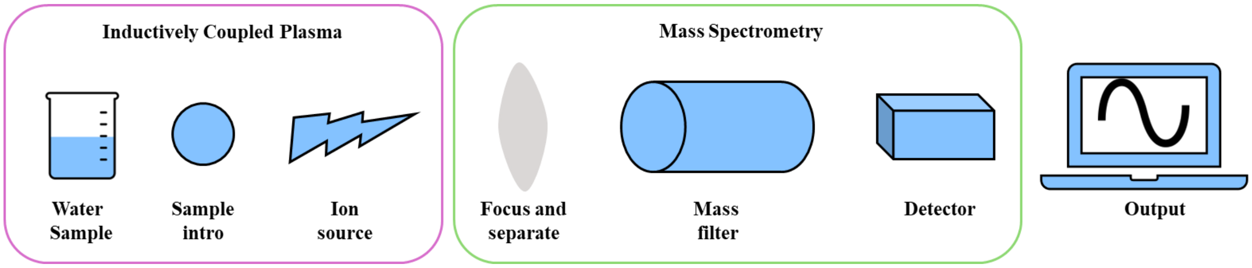

Figure 3.9. Diagram of the principle of Inductively Coupled Plasma Mass Spectrometry (inspired from Agilent, 2025 [134])

3.5 Remineralizing filter

As part of the experimental methodology, the mineral dissolution of both natural and synthetic materials was compared. In addition, the performance of a commercially available option, like the Waterdrop® WD-MNR35 remineralization filter was also evaluated, with its technical specifications summarized in **Table 3.1.** Technical information of the Remineralization Filter (Waterdrop® WD-MNR35)This secondary experiment was conducted to assess the potential of this alternative as well.

Table 3.1. Technical information of the Remineralization Filter (Waterdrop® WD-MNR35)

Parameter	Information
Product Name	Waterdrop Remineralization Filter
Model	WD-MNR35
Flow rate (L/min)	1.05
Contact time (s)	5
Inside diameter (mm)	6.35

As shown in the **Figure 3.10**, the filter is connected using plastic tubing for both inlet and outlet flows. According to the manufacturer's instructions, the filter should be allowed to run for 30 minutes before use, primarily to eliminate any initial turbidity. After this period, a water sample is collected to evaluate the increase in hardness resulting from contact with the filter's internal material.

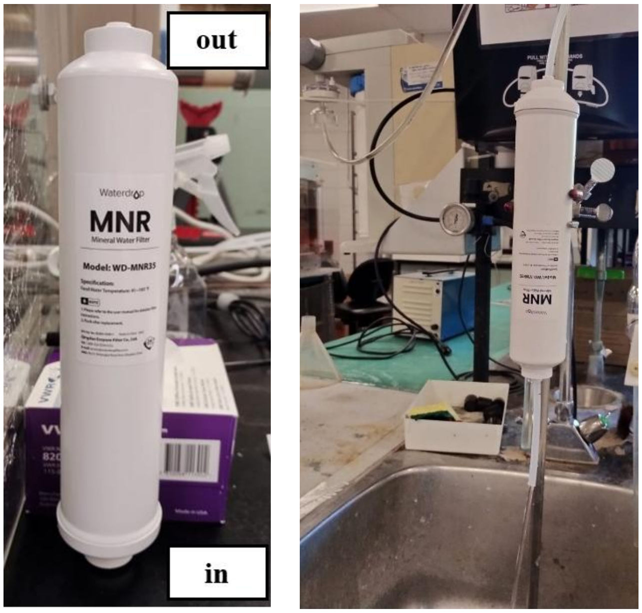

Figure 3.10. Remineralizing filter (on the left) and its setup in the laboratory (on the right).

CHAPTER 4 ARTICLE 1: WATER MINERALIZATION IN RESOURCE-LIMITED LOCATIONS

Presented by: Andres Felipe Sanchez Rendon, Simon Ponton, David Brassard, Emilie Bédard, Jason R. Tavares.

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This article presents the main results of the research project. Supplementary information about the document is presented in Appendix A of the thesis.

Abstract. Water scarcity is a global issue affecting communities worldwide, as seen in events such as the 2018 Cape Town water crisis, 2021 Quebec water restrictions, the recent water shortage in Catalonia, and the Neskantaga First Nations' 30-year struggle without drinkable running water. This highlights the urgent need for sustainable water resource management. Alternative water sources, such as reverse osmosis, rainwater, or atmospheric water harvesting offer promising solutions, though challenges remain concerning the mineralization these types of waters due to their low concentrations of essential minerals like calcium and magnesium. While conventional mineralization methods exist, this study explores an alternative approach by emphasizing the use of native materials to favor resource-constrained communities with limited access to commercial consumables. To assess water mineral dissolution, this work tested five native materials (soil, beige sand, red sand, clay, and gravel), two commercial materials (calcite and Corosex™), and a commercial remineralization filter. Results show that soil (at a dosage of 0.03 g/mL) and red sand (0.25 g/mL) have shown potential as native materials for adjusting and achieving optimal levels of water hardness (182 mg CaCO3/L and 265 mg CaCO3/L, respectively). Furthermore, red sand contains a higher proportion of magnesium ions, an essential nutrient with recognized health benefits, ensuring that World Health Organization mineralization guidelines are met. These native materials show promise for developing a low-consumable mineralization system that could be integrated with non-conventional water technologies, to meet the goal of providing water quality to communities in need, namely in survival conditions.

Keywords. *Water scarcity, Climate change, Atmospheric Water Harvesting (AWH), Mineralizing materials, (Re)mineralization, Water conditioning.*

4.1 Introduction

Every year, 4 billion people face water scarcity at least once per year, a global risk exacerbated by climate change [1]. Recent or current water crises in Cape Town, Catalonia and Canada's First Nations communities reflect the continuing and widespread challenges of access to safe drinking water [5,7,9]. To mitigate the impact of hydric stress, improved water use efficiency and better resource allocation are required [2].

Alternative water sources such as seawater desalination, rainwater harvesting, and atmospheric water harvesting (AWH) are gaining traction in addressing water scarcity [135], helping to expand the water supply and provide alternatives for water access. Seawater desalination is increasingly considered as a viable alternative in semi-arid and coastal regions due to membrane advancements leading to lower energy requirements and enhanced reliability [136]. Rainwater harvesting, effective in areas with annual rainfall of at least 350–390 mm, depends on strategic site selection for optimal performance [137]. AWH has the potential to leverage the 13,000 km^3 of atmospheric freshwater vapor; it is advancing through sorbent-based technologies like nanoporous materials, enabling efficient water capture and release [12–14].

Although alternative water sources offer promising solutions for water access, they present unique challenges related to water quality and health risks [138]. For instance, rainwater, AWH water and water resulting from reverse osmosis contain negligible levels of ions, including calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+) and potassium (K^+). Very low mineral concentrations can affect both health (cardiometabolic health effects) and organoleptic properties (i.e., taste perception) [62]. Numerous epidemiologic studies have reported chronic health effects associated with the consumption of mineral deficient water [51,53,55].

While some studies have assessed potential contamination health risks associated with these alternative water sources [17,18,138,139], few standardized guidelines are available to address both contamination risks and mineral deficiencies [19]. The World Health Organization (WHO) suggests that certain mineral concentrations must be maintained in water [140]; the optimal recommended range for Ca^{2+} is 40–80 mg/L, and 20–40 mg/L for Mg^{2+} [24]. Both minerals need to be present in sufficient quantities to perform many essential metabolic or structural functions in the human body [140].

Calcium levels in tap water are highly variable across water sources in North America (**Figure A.1**). Despite the WHO recommended calcium levels, several North American cities report relatively low concentrations in tap water, with an average value of 21.8 mg/L [141]. This value does not align with the European Directive for demineralized water, which suggests a minimum calcium level of 30 mg/L and an optimal remineralization range [24] (**Table 4.1**). However, the relevance of these thresholds depends on the specific context, particularly in communities with limited resources. The WHO states that drinking water can contribute approximately 5–20% of a person's daily mineral intake, with the remainder obtained from food [140].

Table 4.1. Recommended Mineral Concentrations [24]

Parameter	Unit	Minimum required in demineralized water	Recommended optimum for health
Total Dissolved Solids	mg/L	100	200–500
Calcium		30	40–80
Magnesium		10	20–40

To address the mineral deficiency in alternative water sources, a mineralization system is needed to establish a water quality baseline. Several mineralization processes are well documented in the literature, such as blending with surface water, chemical dosing, or using mineral dissolution with manufactured materials like Corosex™ and calcite [142]. Additionally, commercial mineralizing filters are often suggested to achieve the necessary ion balance in drinking water. Mineral dissolution is advantageous because it can adapt to the needs of a system that works off-grid and has low consumable requirements. Operationally, it is influenced by several factors, including media impurities, particle size, shape and porosity, water acidity, temperature, aqueous CO_2 content, the presence of anions, dissolved metals, and cation exchange [95]. All these factors are relevant when considering water treatment applications, particularly in relation to the mass transfer mechanisms inherent in the materials used in mineralization processes.

One study focused on the mineralization of soft waters using a mixed media contactor composed of $CaCO_3$/MgO in a 95% ─ 5% ratio, with the filtration system operating continuously within a column setup for a total of 720 hours (30 days), maintaining effluent hardness levels close to 30 mg $CaCO_3$/L and effectively removing manganese (Mn) [100]. Additionally, the optimization of various mineralization processes has been investigated through detailed modeling, highlighting the effort and cost involved in implementing different mineralization methods to meet rigorous water quality criteria [142].

Traditionally, commercially available remineralization products include Corosex™ (magnesium oxide, MgO), calcite (calcium carbonate, $CaCO_3$), dolomitic lime (calcium magnesium carbonate, $CaMg(CO_3)_2$), hydrated lime (calcium hydroxide, $Ca(OH)_2$), and sodium bicarbonate ($NaHCO_3$) [81]. Corosex™ and calcite exhibit similar dissolution rates, but their media responses differ. For instance, both dissolve more rapidly at lower pH, though they stabilize at different equilibrium pH levels; additionally, MgO is more soluble than $CaCO_3$. Blending MgO with $CaCO_3$ has been suggested to optimize the $Ca^{2+} - Mg^{2+}$ remineralization ratio and improve pH control [95], though these commercial products still require the delivery of consumables to isolated communities. In such communities, low consumable mineralization solutions utilizing readily available native materials would be ideal. Native materials such as soil and sand are naturally rich in minerals, making them viable for sustainable development applications.

The objective of this study is to confirm that native materials can meet the suggested mineral content requirements while also maintaining other important water quality parameters. Additionally, the system is intended to be applicable to communities with limited access to resources and has potential for use in non-conventional water sources systems. While mineralization of water through contact with various soils has largely been documented namely in the case of subsurface groundwater, the novelty herein resides in the study of how native resources can be used for mineralization in remote locations, as a complement to novel water sources (such as water harvested from the atmosphere, or derived from reverse osmosis).

4.2 Material and Methods

4.2.1 Materials

Natural materials such as Black Earth soil from Charbonneau Floral, beige Play Sand and Beach Pebbles gravel from Garden Club and pebble-shaped Hydro Clay from Brockytony were sourced from local suppliers. Red beach sand was collected in Prince Edward Island (Canada) by a local collaborator. Sterilization of natural samples was performed at 120-130°C for at least 24 h**.** The soil samples were sieved through a 1 mm mesh to remove large pieces of organic components and to ensure a consistent particle size throughout the experiment. Corosex™ was sourced locally, and calcite was provided by a collaborator. A commercially available Waterdrop® Remineralization Filter WD-MNR35 was also evaluated. Ultrapure water (Milli-Q™), with a resistivity of 18 MΩ/cm, was used as a surrogate for low ion concentration water.

4.2.2 Material Characterization

Three complementary methods were used to assess particle size, surface area, and density of the natural materials. Dry sieving (ASTM C136/C136M) was applied, a mass of 300 g was used for the granulometric analysis of fine materials, employing sieves between 1 mm and 120 µm. For coarser fractions, 600 g of clay pebbles and 5 kg of gravel were analyzed using a coarser sieve range between 2.36 mm and 19 mm, ensuring adequate representativity of the bulk material. ImageJ software was used to analyze the shape and equivalent diameter of 81 coarse particles from gravel and clay pebbles. For fine particles (<2 µm), laser diffraction was performed using a Malvern Mastersizer 3000. Surface area was obtained from this analysis or estimated using density values measured with a helium gas pycnometer (AccuPyc II 1340) at 23.5–24.8 °C. Elemental analysis was performed using inductively coupled plasma mass spectrometry (ICP-MS) at Bureau Veritas for the detection of major and trace elements in the native materials composition.

4.2.3 Experimental conditions

Each mineralizing material was mixed with Ultrapure water at a ratio of 25 g of material per 100 mL of water in a 250 mL Erlenmeyer. The flask was pre-cleaned with soap and hot tap water, then rinsed seven times with Ultrapure water to prevent contamination. Soil samples were also tested at 3g per 100 mL of water. The materials were tested in batches and exposed for different contact times: 15, 30, 45, and 60 min. During each test, all samples were stirred at a mixing speed of 200 rpm with a shaker table. After leaching, the samples were filtered using Büchner filtration with a grade 5 filter paper (pore size: 2.5 µm); a blank sample was included to ensure the filter and process did not affect mineral measurements. All materials were tested in triplicate.

4.2.4 Cyclability of the materials

Soil was the only material evaluated for cyclability, in triplicate. The test included four 15-min contact time rounds. The same 25 g soil sample was used for the whole test, and it was heated between 120 –130°C for at least 24 h prior to each round. Every round, 100 mL of Ultrapure water was added to the soil sample. The same stirring and filtration protocol described above was used for each round.

4.2.5 Water Quality analysis

Minimal water quality assessment is based on suggested values found in the literature (**Table A.1**). The water obtained after contact with the mineralization materials and subsequent filtration was analyzed for baseline water quality parameters, following the protocols outlined in the *Standard Methods for the Examination of Water and Wastewater* [47]. Each water sample was analyzed on the same day of collection to determine pH (Electrometric Method 4500, AR25 pH Meter), dissolved organic carbon (DOC) (Standard Method 5310, Sievers M5310 C Analyzer), conductivity (Standard Method 2510, Mettler Toledo SevenDirect SD30/InLab® 731-ISM probe), turbidity (Standard Method 2130, Hach TL2300), UV absorption at 254 nm (Standard Method 5910, with Ocean Optics spectrometer USB4000 – XR1 – ES), and total dissolved solids (TDS) (Standard gravimetric Method 2540).

The concentrations of Ca^{2+} and total hardness were determined by titration (Standard Method 3500-Ca, using the Patton-Reeder indicator instead of the murexide indicator, and Standard Method 2340 C). Mg^{2+} concentration was then calculated based on the values of Ca^{2+} and total hardness (Calculation Method 2340 B). A duplicate of each sample was acidified ($pH < 4$) for later analysis via atomic absorption spectrophotometry to determine the concentrations of Ca^{2+}, Mg^{2+}, Na^{+}, Si^{4+}, Al^{3+}, and Fe^{2+} (PerkinElmer Pinnacle 900F).

All water quality tests were conducted in Ultrapure water as a blank and for comparison purposes. Water from a laboratory AWH prototype and Montreal tap water were analyzed for Ca^{2+}, Mg^{2+}, Na^{+} concentrations via atomic absorption spectroscopy as points of comparison.

4.3 Results and Discussions

Seven possible mineralizing materials were evaluated, including five native materials (soil, red sand, beige sand, gravel, clay), and two manufactured materials commonly referenced in water treatment literature (calcite and Corosex™). The primary goal was to evaluate materials that could serve as mineralization alternative while meeting the following criteria: a low-consumable system using locally available materials, and capacity to increase ion levels in water.

Native materials refer to locally available substances whose particle characteristics can be compared against soil classification standards to better understand their composition. Examining the surface area to volume ratio is particularly relevant, as fine materials tend to have a higher surface area, which enhances their contact with water and increases the potential for mineral leaching. However, surface interactions also depend on the chemical nature of functional groups at the material surface, which facilitate ion exchange and contribute to water remineralization. To investigate these aspects, a particle size distribution analysis was conducted alongside an evaluation of structural properties as shown in **Table 4.2** and in the supplementary information (**Table A.3, A.4**).

Table 4.2. Granulometric analysis and physical-structural properties of native materials

Particle size distribution	Sieve (µm)				
	Soil	Red Sand	Beige Sand	Clay	Gravel
Dx (90)	1197	397	390	11,145	15,982
Dx (50)	510	270	189	7,725	11,755
Dx (10)	172	180	50	5,262	7,457
Dx (3,2)	322	257	85	7,357	12,206
Density (kg/m^3)	1,580 ± 0.3	2,640 ± 0.5	2,500 ± 0.4	2,280 ± 1	2,700 ± 0.6
Surface Area (m^2/kg)	11.76 ± 1.08	8.86 ± 0.14	26.37 ± 9.94	0.50 ± 0.1	0.25 ± 0.1

Dx(90), Dx(50), and Dx(10) parameters provide a representative characterization of the material's particle size distribution, a wide range of particle sizes was observed among the native materials. For the soil, red sand, and beige sand samples, primary particle size corresponds to soils with coarse, medium, and fine sand textures, as per the Canadian soil classification system [104]. In contrast, the clay and gravel samples lie closer to the cobble limit. In addition, D[3,2], or surface area mean diameter, represents the mean particle size weighted by surface area. It is particularly relevant for surface-driven processes like ion exchange, as it estimates the available surface area for interaction.

Physical and structural measurements such as density and surface area offer further insights into material structure. As stated earlier, finer particles generally exhibit a higher surface area, enhancing their potential for ionic exchange. However, a higher density suggests a more compact particle arrangement, indicating lower porosity and reduced water contact capacity. Hardness was the initial key parameter considered in its capacity as an indicative measure of the presence of Ca and Mg in water. The Ca, Mg and Na concentrations in five water sources were assessed (**Table 4.3**). Tap water was used a positive reference for hardness and reverse osmosis water, rainwater, atmospheric harvested water, and ultrapure water were representative of low mineral content water.

Table 4.3. Ca^{2+}, Mg^{2+} and Na^{+} content of AWH water, ultrapure water, and Montréal tap water. Reverse osmosis water and rainwater values were taken from the literature.

Sample	**pH**	**Ca^{2+} [mg/L]**	**Mg^{2+} [mg/L]**	**Na^{+} [mg/L]**
AWH water	6.32 ± 0.17	0.28 ± 0.04	0.05 ± 0.015	0.36 ± 0.012
Milli-Q™ ultrapure water	5.85 ± 0.3	0.06 ± 0.02	< 0.02	0.11 ± 0.04
Reverse Osmosis water [143]	4.00 — 7.80	0.46	0.37	37.0
Rainwater [144]	6.4	0.65	0.14	0.56
Tap Water – Montréal*	7.60 ± 0.2	32.2 ± 0.035	8.12 ± 0.015	14.6 ± 0.05

* Tap water data collected on August 20, 2024

4.3.1 Effect of native and commercial materials on mineral content of water

Hardness and mineral composition after exposure to materials

Once the mineralizing materials was put in contact with the ultrapure water, saturation was reached in less than 15 min for all tested materials (**Figure 4.1**). Soil increased the water total hardness the most and its saturation did not increase with longest contact times (**Figure A.2**), while gravel proved to be the least effective. Red sand and Corosex™ exhibited intermediate effectiveness, with values about an order of magnitude lower than soil. Calcite and beige sand contributed to hardness the least.

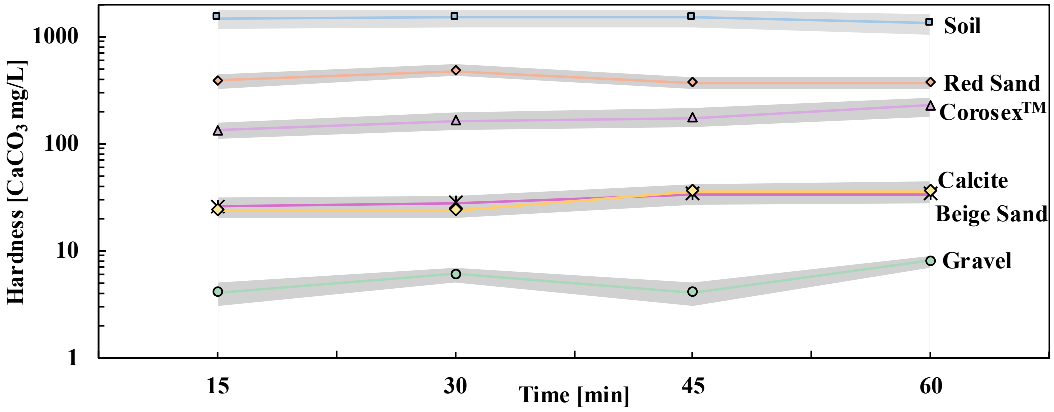

Figure 4.1. Comparison of leachability trends across materials at different contact times (200 rpm, 25g/100ml, n=3, grey overtones represent measurement uncertainty, lines introduced to guide the reader's eye)

The concentrations of Ca, Mg, Si, Al and Fe in water were measured after mineralization with the studied native materials (**Figure 4.2**). Ca was the predominant ion released from most mineralizing materials. Al was below detection limit for all tested samples.

An important factor to highlight in the red sand sample is the higher proportion of Mg ions compared to Ca ions, which may offer additional benefits. While Ca is typically recommended in higher proportions, Mg also plays a crucial role in health, but its intake is more limited in food [95].

Although Ca and Mg are the main contributors of water hardness, the presence of other multivalent cations can contribute to the total hardness [47]. In some samples, high concentrations of Fe^{2+} were detected, ranging from 7.09 to 12.5 mg/L. These results emphasize the importance of understanding the complete ion composition, beyond just Ca and Mg. Since natural samples can be heterogeneous in composition, an additional analysis using ICP-MS was carried out to identify and quantify the ions present (**Appendix B**). This approach enabled the establishment of an ionic balance between the solid materials and their leachates, revealing that although beige sand and clay contained high levels of target ions such as calcium and magnesium in their elemental composition, they exhibited lower leaching efficiency compared to red sand and soil. Heavy metals were also detected in the composition of native materials (e.g., Pb, As, Cd, Cr, Ni), raising concerns due to their potential health risks if released into drinking water [145] However, the mobility of these metals is strongly influenced by water quality parameters such as temperature, dissolved oxygen, and pH [146]. For instance, at temperatures ranging from 31.4 to 39.0 °C, heavy metals tend to accumulate in sediments, whereas dissolved oxygen levels outside the range of 5.3 to 8.0 mg/L can increase their solubility. Moreover, maintaining pH levels between 6.5 and 8.0 minimizes the solubility and mobility of heavy metals [114]. Therefore, controlling these parameters is essential when assessing the risks associated with heavy metal release.

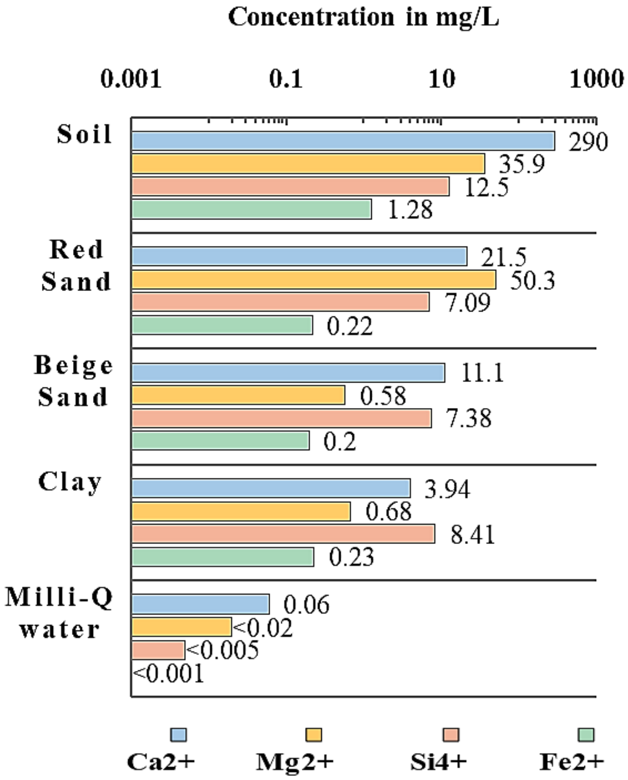

Figure 4.2. Concentration of select ions after contact with mineralizing materials (25 g/100 mL, contact time 15 min).

Results of the commercial options

All three tested commercial solutions (calcite, Corosex™, and a remineralization filter) led to an increase in Ca and Mg concentration (**Figure 4.3**). Levels remained lower for the remineralization filter and calcite compared to some natural materials evaluated. Additionally, the final ion concentrations for these two commercial options did not reach those found in municipal tap water, such as in Montréal (**Table 4.3**).

Among the manufactured materials, Corosex™ showed significant potential for mineralization, with notable mineral release. Despite its theoretical composition of 98% MgO [147], the amount of Ca ions present after leaching was higher than that of Mg. This suggests that, despite the high Mg content in the material, its ability to release Mg ions are lower than expected. This discrepancy may be due to the 2% impurities in Corosex™, as studies suggest that small amounts of calcium oxide (CaO) in caustic magnesia influence the dissolution process [95]. Results show that calcite and the remineralization filter did not fully align with the expected optimal ion concentration for health, as outlined in **Table 1.1.**

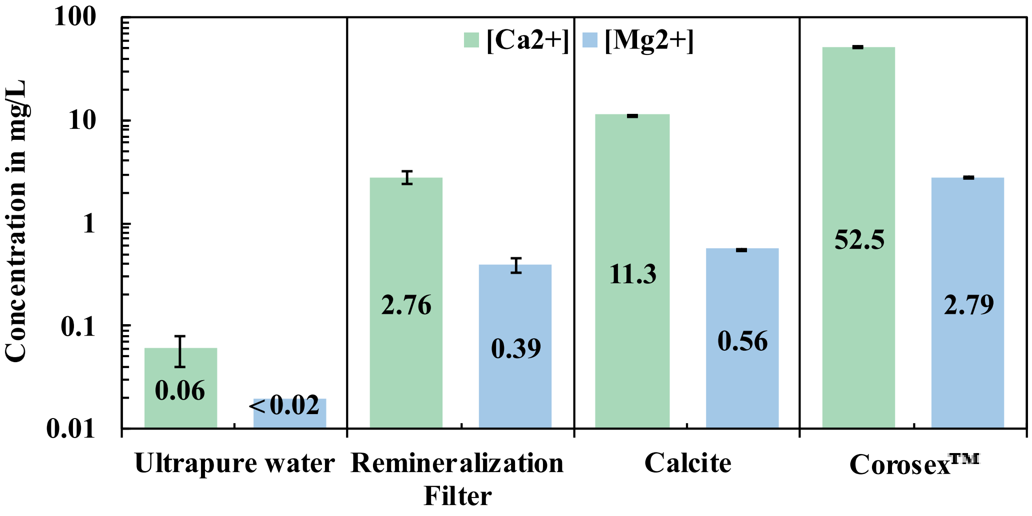

Figure 4.3. Evaluation of the performance of a remineralizing filter, calcite and Corosex™ to add calcium and magnesium ions to the Milli-Q™ water. The filter water sample was taken after 30 min at a flow rate of 1.05 L/min, while calcite and Corosex™ concentrations were 25 g/100 mL for 15 min contact time (n=3).

4.3.2 Water quality baseline after contact

In addition, seven principal parameters are selected for investigation to assess water quality. Baseline water quality parameters were assessed for water samples after 15 min exposure to materials and subsequent filtration (**Figure 4.4, Table A.2**)

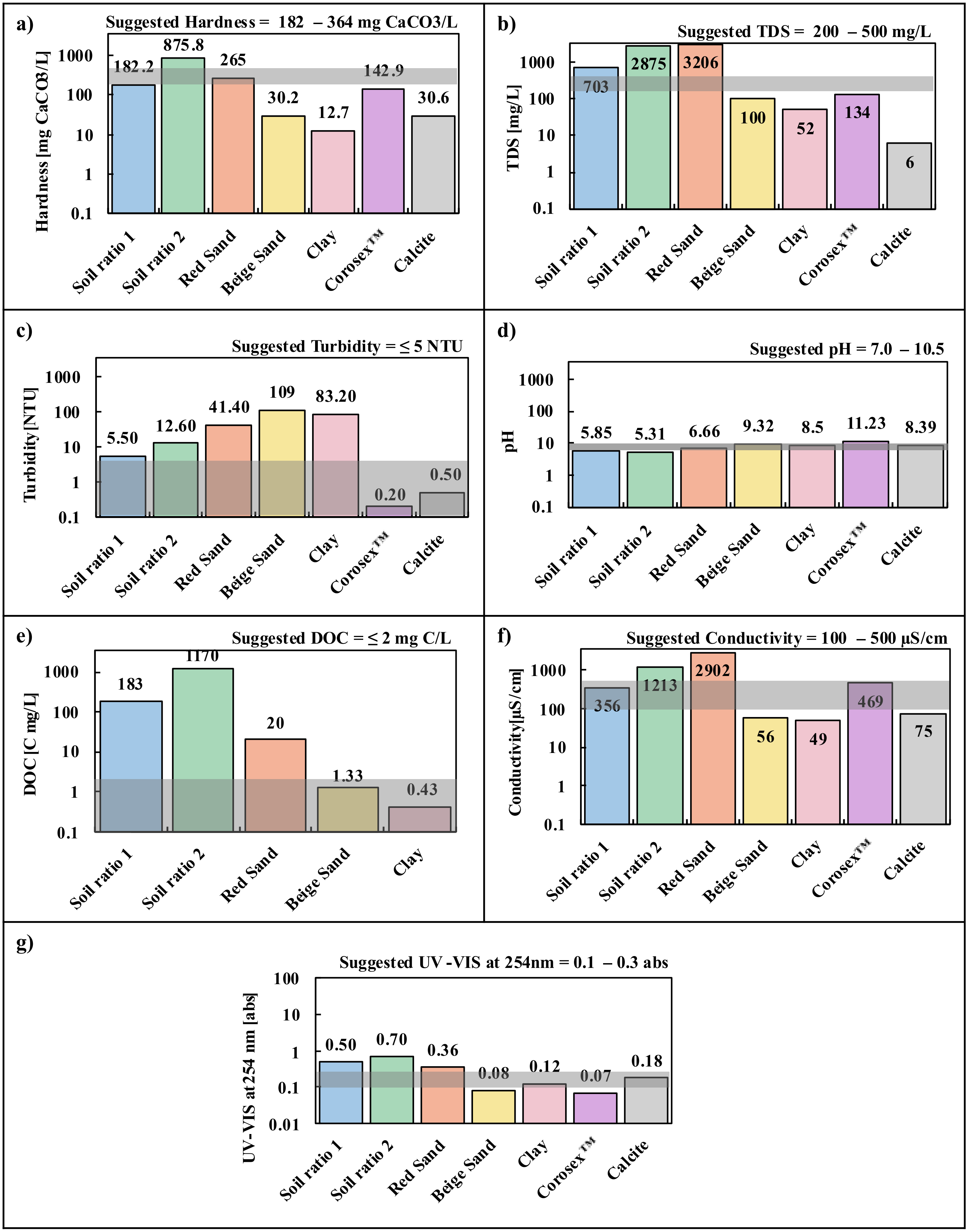
a)
Suggested Hardness = 182 – 364 mg CaCO3/L
Hardness [mg CaCO3/L]
1000
100
10
1
0.1
182.2
875.8
265
30.2
12.7
142.9
30.6
Soil ratio 1
Soil ratio 2
Red Sand
Beige Sand
Clay
Corosex™
Calcite
b)
Suggested TDS = 200 – 500 mg/L
TDS [mg/L]
1000
100
10
1
0.1
703
2875
3206
100
52
134
6
Soil ratio 1
Soil ratio 2
Red Sand
Beige Sand
Clay
Corosex™
Calcite
c)
Suggested Turbidity = ≤ 5 NTU
Turbidity [NTU]
1000
100
10
1
0.1
5.50
12.60
41.40
109
83.20
0.20
0.50
Soil ratio 1
Soil ratio 2
Red Sand
Beige Sand
Clay
Corosex™
Calcite
d)
Suggested pH = 7.0 – 10.5
pH
1000
100
10
1
0.1
5.85
5.31
6.66
9.32
8.5
11.23
8.39
Soil ratio 1
Soil ratio 2
Red Sand
Beige Sand
Clay
Corosex™
Calcite
e)
Suggested DOC = ≤ 2 mg C/L
DOC [C mg/L]
1000
100
10
1
0.1
183
1170
20
1.33
0.43
Soil ratio 1
Soil ratio 2
Red Sand
Beige Sand
Clay
f)
Suggested Conductivity = 100 – 500 µS/cm
Conductivity [µS/cm]
1000
100
10
1
0.1
356
1213
2902
56
49
469
75
Soil ratio 1
Soil ratio 2
Red Sand
Beige Sand
Clay
Corosex™
Calcite
g)
Suggested UV-VIS at 254nm = 0.1 – 0.3 abs
UV-VIS at 254 nm [abs]
100
10
1
0.1
0.01
0.50
0.70
0.36
0.08
0.12
0.07
0.18
Soil ratio 1
Soil ratio 2
Red Sand
Beige Sand
Clay
Corosex™
Calcite

Figure 4.4. Comparison of seven baseline water quality parameters for mineralizing materials, with their suggested values for each parameter. a. Hardness, b. Total Dissolved Solids (TDS), c. Turbidity, d. pH, e. Dissolved Organic Carbon (DOC), f. Electrical Conductivity, and g. UV-Vis absorbance at 254 nm. The ratio of material to water was 25 g/100 mL, except for soil ratio 1, which was 3 g / 100 mL; the exposure time for all samples was 15 min. For each sample, water was filtered prior to measuring these parameters. The grey area corresponds to suggested values for each parameter, indicated for comparison (references in **Table A.1**). Each panel (a–g) corresponds to the respective water quality parameter measured in the study.

As observed in previous experiments, soil samples exhibited the highest hardness levels (**Figure 4.4a**). Even at the lowest tested ratio (0.03 g/mL), its hardness remained within the suggested range, indicating its potential to supply minerals essential from a health perspective [24]. Red sand was also promising as a natural alternative for adding hardness. Similarly, soil and red sand had the highest contribution to TDS, which may result in negative perception since excessive TDS can affect water quality [57]. In contrast, the other materials remained below 100 mg/L TDS, a range often associated with bitter, dry, and rough taste in water [62]. Red sand demonstrated the highest conductivity, followed by soil and Corosex™, confirming the presence of ions and exhibiting their strong mineralization potential. In contrast, materials like calcite, beige sand, and clay contributed minimally to conductivity.

All natural materials tested, after the Büchner filtration method, exceeded the suggested turbidity limit of < 5 NTU [148], indicating the presence of suspended particles like dirt, silt, and organic matter. Improved filtration methods can remove suspended particles and reduce the turbidity within acceptable limits. The soil sample was slightly above the threshold, while the manufactured materials remained within the recommended range. UV-Vis absorbance at 254 nm was measured as an indicator of color, precursors of trihalomethanes (THMs), and organic content. Almost all materials exhibited UV-Vis absorbance outside the recommended range of 0.1 - 0.3 abs. [149,150], except for clay and calcite. However, soil and red sand showed higher values, indicating the potential presence of aromatic compounds.

Soil exhibited a slightly acidic pH, falling outside the suggested range 7.0–10.5 [151]. Beige sand showed higher pH values, while Corosex™ exceeded the recommended limits. pH conditioning may be necessary for most native materials. Potential solutions include mixing with materials that exhibit alkaline behavior or considering different thermal treatments for specific natural samples, which have been shown to increase the pH of natural soil [152].

Dissolved Organic Carbon (DOC)

Soil showed the highest organic load among the materials, which deviated from the expected limits of ≤ 2 mg/L [153]. Thermal treatments, such as those applied prior to experiments for the purposes of sterilization, can alter the properties of soil; lower temperatures over extended periods can produce effects similar to those of higher temperatures in a shorter time [154]. At 100 °C, some studies report a 5-12% increase in organic matter due to the incorporation of carbonized compounds [155], while others observe carbon loss and volatilization between 100-200 °C [156]. Organic matter can decrease by up to 85% at 200-300 °C [157], reaching 99% degradation at 450 °C for 2 hours or 500 °C for half an hour [158]. While high temperatures reduce organic matter and increase soil pH, heating at 300 °C also significantly decreases cation exchange capacity [152]. Different heat treatments and exposure times could be explored to assess the response of the specific soil sample in terms of mineralization and its impact on water quality after contact, but this falls outside the study's objectives since fine control of those high temperatures are not feasible under survival conditions. In this case, the temperature and time used did not result in a decrease in organic matter or an increase in water pH. Red sand also exhibited high DOC values. The organic load could be further reduced by activated carbon or coagulants, especially in materials with high organic content. Beige sand meets the criteria for DOC, suggesting it is the only natural sample evaluated that does not pose a significant risk for the development of organic load in water. Corosex™ and calcite were not tested as they are inorganic compounds with negligible contributions to organic carbon content.

Overall, the soil at 0.03 g/mL had the greatest impact on hardness, ion release, and conductivity, although its pH, DOC, and UV-Vis levels deviated from the recommended ranges. Red sand showed promise for hardness and TDS but exhibited high levels of DOC, pH, and UV-Vis. Beige sand had a lesser impact on TDS and conductivity but performed well within the expected pH and DOC ranges. Clay and calcite had minimal effects on water quality parameters, with low ion release, but helped maintain pH within the expected range. Corosex™ demonstrated good ion release patterns, but strong pH overcorrection suggests that careful consideration of its ratio is necessary. All native materials tested exceeded the recommended turbidity range, while the manufactured materials showed the best performance in this regard. Overall, no single material met all the water quality criteria without requiring further adjustments or conditioning, especially for materials easily accessible for resource-limited communities.

While challenges exist, under survival conditions the line between desired and necessary parameters becomes thin and variable. This approach, using native materials, offers a promising starting point for maintaining access to basic water quality. In contrast to purely aesthetic aspects, vital factors such as optimal mineral content can be effectively achieved through native materials. **Figure 4.5** presents a flow chart outlining the criteria for selecting native materials used in water mineralization, based on key parameters that allow measuring mineralization potential through leaching and saturation capacity, the presence of essential ions, along with the basic water quality criteria. A minimum of 100 mL of low-mineral water is initially required to account for absorption losses, especially with materials like soil, which can retain 10–15% of the water used. The components that are not yet fully developed are included in the gray box, most notably the microbiological considerations, which are beyond the scope of the present study.

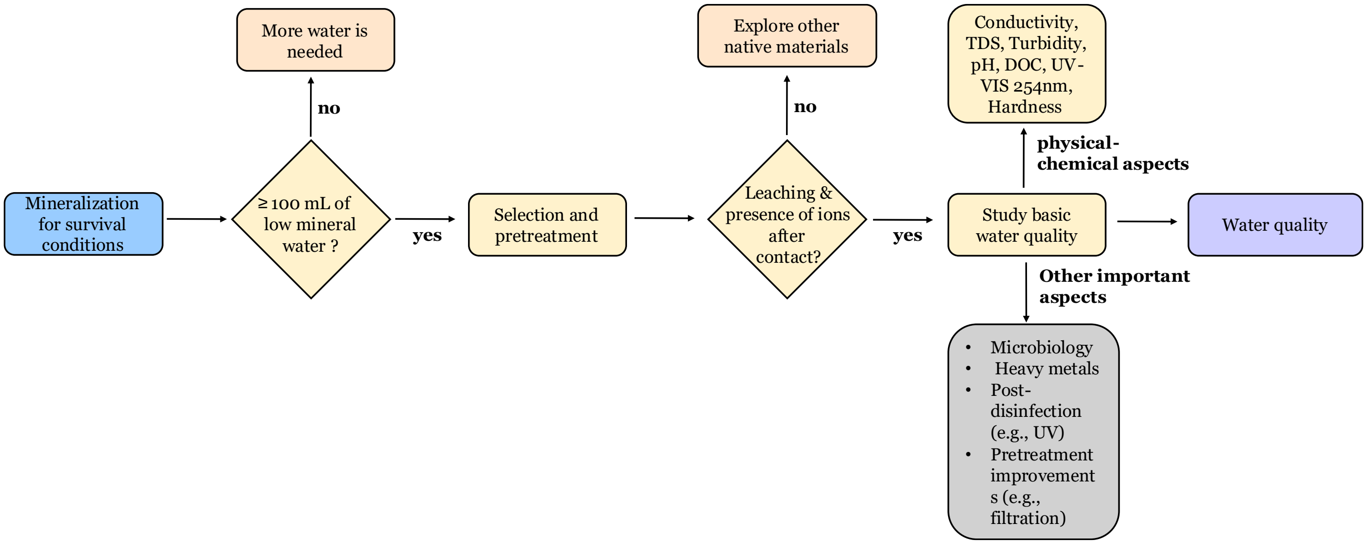

Figure 4.5. Native material selection algorithm for water remineralization in low resource context.

Based on the results obtained for natural materials, an approach to a mineralization protocol is proposed. If 100 mL of low-mineral water is available, it is possible to select either 3 g of soil or 25 g of red sand. Both options allow for water with an adequate concentration of key ions, such as

Ca and Mg, within the recommended range. While there are challenges to consider, this approach represents a promising starting point for water mineralization in survival scenarios.

4.3.3 Exploring cyclability of soil

Since maximum saturation could be achieved in 15 min, the potential to reuse the soil sample was studied. Soil was retained for cycling tests due to its potential as a natural mineralizing material and its ability to contribute the highest ion release to the water.

Figure 4.6 illustrates the progression of water hardness over four successive cycles. The results show an initial increase in hardness after the second 15 min cycle, followed by a gradual decrease in subsequent cycles. This suggests that while the soil initially improves its mineralization capacity through ion release, but performance declines over repeated use. This might be related to the repeated heating of the material in between each cycle. Heat exposure of the soil is known to progressively reduce ion exchange capacity [159].

Similarly, the anomalous increased ion release observed in the second cycle could also possibly be explained by the repeated thermal treatments applied to the same soil sample before each hardness test. This heating could have further increased soil porosity in the second round until reaching a saturation point, exposing more surface area and allowing maximum ion leaching, followed by a decline upon reaching its capacity limit. This behavior aligns with studies on heat-induced soil changes, which show that high temperatures reduce organic matter, porosity, among other properties [160]. As porosity decreases with repeated heating, the effective surface area may temporarily increase, enhancing short-term ion release.

The heat treatment applied between cycles was not aimed at enhancing mineralization but was rather a measure to ensure experimental reproducibility. This step helped to eliminate moisture and to adhere to the conditioning protocol of the first-run native samples. Based on the observed trend of decreasing hardness concentration, it can be extrapolated that after five cycles, water hardness will reach the recommended health range. Beyond this point, ion release is expected to diminish.

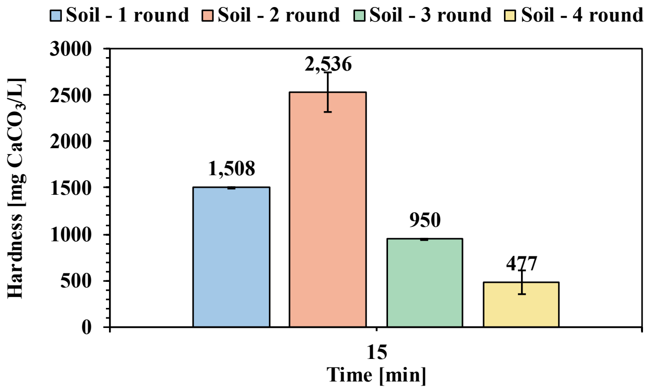

Figure 4.6. Hardness trend of ultrapure water after 15-minute contact with soil (0.25 g/mL) across four reheating cycles using the same sample and ratio (n=3).

4.4 Conclusions

In an effort to explore alternate remineralization strategies for isolated, water-stressed communities drawing water from alternative sources such as AWH or reverse osmosis water, low consumable approaches employing native resources were tested. Soil (0.03 g/mL) and red sand (0.25 g/mL) showed particular promise as natural materials capable of adjusting water hardness, achieving values of 182 mg $CaCO_3$/L and 265 mg $CaCO_3$/L, respectively. These levels fall within the optimal health range defined by the WHO. Additionally, both materials exhibit rapid ion release kinetics, reaching maximum saturation within 15 min of contact time (with potential for cycling), making them efficient candidates for mineralization processes. A key finding regarding red sand is its higher proportion of leached Mg ions compared to Ca. Mg is an essential nutrient with recognized health benefits, yet its intake is often insufficient.

Despite their potential, native remineralization sources lead to other water quality parameters outside of the recommended ranges, such as pH, dissolved organic carbon (DOC), and UV-Vis absorption at 254 nm. To make their application viable (beyond strict survival conditions), different strategies should be explored. Combining different materials in defined ratios, if available, could contribute to achieving balanced water quality. Additionally, incorporating certain materials shows potential for reducing organic matter. However, further evaluation is needed to understand their interaction with ions in the medium, particularly whether they capture, alter, or have no significant effect on ion concentrations.

It is important to highlight that this study aimed to evaluate key water quality parameters under a baseline framework in service to communities with limited access to consumables. While the study provides basic water quality insights, further research could include microbiological testing and a more comprehensive water analysis beyond the proposed parameters, as well as an assessment of how this approach could operate with a disinfection stage. Beyond providing alternative solutions to improve the quality of water produced by non-conventional sources, the findings of this project could have potential applications in food production and agriculture, particularly in cases where mineral content adjustments are needed to enhance water quality across multiple sectors.

One of the key motivators of this work is to habilitate remote communities to mineralize water from alternate sources, in survival conditions, in the absence of commercially available mineralization products (such as calcite, corosex™ or point-of-use mineralization filters). Indeed, remote communities must deal with significant shipping costs for the transport of cargo; for example, the supplementary cost to ship materials to the Canadian northern territories is equivalent to a 45 to 190% surtax [161]. Therefore, the goal is to offer a local and accessible solution that improves water security in these regions with constrained resources.

Acknowledgements

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CRediT author statement contributions

Andres Felipe Sanchez Rendon: Writing- Original draft preparation, Investigation, Visualization. **David Brassard:** Writing - Review & Editing, Visualization. **Simon Ponton:** Writing - Review & Editing, Visualization. **Emilie Bédard:** Supervision, Writing - Review & Editing, Conceptualization. **Jason R. Tavares:** Supervision, Writing - Review & Editing, Conceptualization, Funding acquisition.

Declaration of generative AI in scientific writing

Statement: During the preparation of this work the author(s) used ChatGPT, DeepLWrite to improve language, grammar checking and comprehensibility. After using this tool, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

CHAPTER 5 GENERAL DISCUSSION AND ADDITIONAL RESULTS

5.1 Summary of the work

Non-conventional water sources, such as AWH water, have emerged as a promising solution to support underserved communities facing water scarcity. So far, most efforts have focused on improving access, with limited attention to the quality of the harvested water. The literature highlights potential contamination from the harvesting equipment or the surrounding air and emphasizes the similarity of AWH water to distilled water. This raises the need for conditioning processes to make this water drinkable, particularly by ensuring an optimal ionic composition, which affects health and taste, an important approach for the target communities.

Although various mineralization strategies have been widely documented, including direct chemical dosing, mixing with hard water, and mineral dissolution, the latter is especially well-studied in the literature with manufactured materials such as calcite or Corosex™. However, from the author's knowledge, there is no mention of survival-based mineralization approaches using locally available natural materials. The use of soils and sediments as mineralizing agents for AWH water represents the innovative aspect of this research project, which has demonstrated potential in the following points:

- Resolves a low consumable dependency, making it suitable for decentralized water production and accessible for the target communities.
- Highlights the distinction between desirable and necessary: despite some aesthetic considerations, native materials offer a promising baseline for maintaining essential mineral content in drinking water, a critical aspect for communities in survival conditions.
- Exhibits efficient leaching behavior, reaching saturation within approximately 15 minutes and maintaining performance over up to four reuse cycles, based on results from one representative native material.
- Shows potential for broader applications, involving low mineral water sources, such as RO treated water and roof harvested rainwater. It can also be applied in sectors like agricultural or food production, where adjusting mineral water content is needed to meet specific water quality requirements.

However, certain limitations need to be clarified and are presented in the following section.

5.2 Work limitations

5.2.1 Atmospheric Water from a laboratory prototype

At the beginning of the project, the aim was to use AWH water generated by the laboratory prototype. However, operating parameters are not fixed, as both the AWH device and the sorbent material are still under improvement, leading to fluctuations in performance. Typically, the experimental requirements for leachability, cyclability, and basic water quality assessments demanded significantly higher daily volumes, exceeding two liters, which surpassed the production capacity of the current AWH system.

Additionally, the air source used by the prototype is a humidifier filled with distilled water, rather than ambient atmospheric air. This creates ideal, controlled laboratory conditions that do not reflect a real environmental variability. As mentioned above, it has been assumed that AWH water has similarities to deionized water. However, **Table 5.1** presents a comparative analysis of additional parameters for atmospheric water generated from a desiccant material (reported in the literature) and the laboratory-grade deionized water used in this study.

Table 5.1. Comparing Milli-Q™ water and reported AWH water collected values [19]

Parameter	Units	Ultrapure Water (Milli-Q™)	AWH Water Type A*	AWH Water Type B**
pH	–	5.85	5.8	4.7
Dissolved Organic Carbon (DOC)	mg/L	0.21	5.8	26.7
Conductivity	µS/cm	0.8	13.1	57.4
Turbidity	NTU	0.01	0.41	0.30
UV-Vis at 254 nm	abs/cm	0.062	0.004	0.032
Dissolved Solids (TDS)	mg/L	0	ND	ND
Water Hardness	mg CaCO3/L	0.234	ND	ND

* AWH water samples from a AWH collector working in an office building.

**AWH water samples from a AWH collector working in a residential house.

Although specific values for target cations such as Ca^{2+} and Mg^{2+} were not reported, the study states they were measured using ion chromatography (Metrohm 930 Compact IC), with a detection limit for metals of approximately 1 µg/L, so they were not detected. The most prevalent ions were nitrate, nitrite, sodium, and chloride, with concentrations ranging from 0.04 mg/L to 2.3 mg/L [19]. In comparison, the reported sodium levels in tap water from Montreal were 14.6 mg /L, as shown in **Table 4.3**.

While deionized water can serve as a representative low-ion water matrix, its composition does not completely match the values for other reported parameter of AWH water, excluding pH in the case of AWH water type A. This suggests that although ionic concentrations are low, the harvested water can vary depending on environmental conditions, suggesting an influence of air quality on the final water composition. As such, the experiments were conducted under certain ideal conditions, which limits the direct applicability of the findings to real-life scenarios.

5.2.2 Microbiological aspect of water quality

Previously, a set of basic physicochemical water quality parameters was discussed. This is closely linked to another critical aspect: microbial analysis. Complete drinking water quality assessments go beyond UV-Vis at 254 nm and organic load to also address microbiological contamination. Water can act as a vector for pathogens, including viruses, parasites, bacteria, and fungi, which can pose serious health risks and increase treatment costs [162].

The basic water quality analyses conducted did not include microbiological testing, such as heterotrophic plate count (HPC), which is used to quantify heterotrophic bacterial colonies in each water sample. As a result, there is limited understanding of the microbial safety of the water after contact with the mineralizing materials, especially those of natural origin. According to Zeng et al., 2024, a value of 0 CFU/mL is reported from 1 mL of sample plated on agar and incubated at 30 °C for 48 h. The device produced 3.6 L/day of AWH water [19].

However, concerns arise when using natural materials as a source of mineralization. Soil, in particular, showed high COD levels, which can promote microbial growth and pose health risks. In fact, at the beginning of the experiments, a sample without thermal pretreatment and with a high material-to-water ratio (>0.25 g/mL) was intentionally left for three days, during which visible microbial contamination was observed.

The results shown in **Figure 5.1**. indicate microbial presence. Several hypotheses could explain this, including possible external contamination from ambient air in the fume hood or the lack of thermal pretreatment of the material that was put in contact with water. However, no equivalent tests were conducted on samples that underwent thermal treatment. Therefore, without a direct comparison, microbial growth cannot be conclusively attributed to the absence of pretreatment. Additional microbial analyses are required to identify the cause.

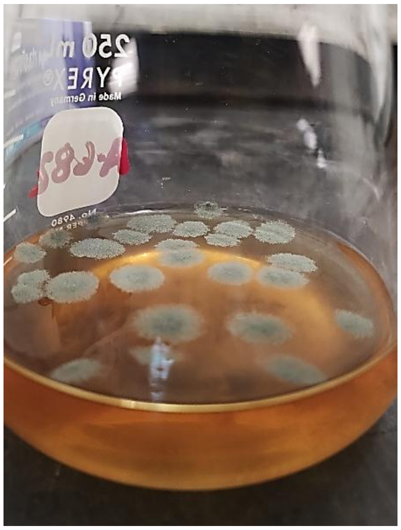

Figure 5.1. Microbial presence in a water sample exposed to a non-thermally pretreated mineralizing material. The sample was left in a fume hood for 3 days prior to observation.

Potential solutions to microbial contamination include filtration and disinfection. Ultrafiltration membranes, with pore diameters ranging from 0.1 to 0.001 µm, have been reported in the literature to retain a wide range of contaminants, including pollen, bacteria, viruses, sugars, and even monovalent ions [163]. However, this may compromise the goal of achieving optimal mineral content, making pore size selection critical. Another approach is disinfection using UV-LEDs, which not only inactivate pathogens without generating harmful disinfection by-products but also offer low maintenance and power requirements, aligning well with the objective of a decentralized production of the AWH water systems [164,165].

However, a relevant point of concern in these systems is biofilm formation, influenced by factors like materials and nutrient release from mineralization substrates. Biofilms can compromise water quality through bacterial detachment and have also been linked to pipe corrosion and fouling in distribution systems [166]

5.2.3 Natural materials

The natural materials evaluated in this project (**Figure 5.2**) represent only a small subset of the wide variability of local resources in terms of elemental composition, particle size, color, morphology, ion exchange capacity, and leaching mineralization potential. A limitation of this study is the lack of detailed physical characterization, including particle size distribution, porosity, specific gravity, bulk density, surface area, and other mechanical properties commonly assessed in manufactured materials, which can help clarify how structural characteristics influence mineral release and other basic water quality parameters.

In fact, a study on a natural material known as Maifan stone, which is a traditional Chinese mineral rich in soluble elements, investigated the mineral extraction using different mechanical methods such as grinding and soaking. Vibratory wet grinding was found to extract more minerals compared to soaking after dry grinding. Key influencing factors included grinding time and solid-liquid ratio, highlighting wet grinding as a method for enhancing mineral extraction [167]. This suggests that modifying mechanical properties such as particle structure through grinding could improve leaching performance in certain natural materials .

Figure 5.2. Four native materials as mineralizing agents: soil, beige sand, red sand, and clay (left to right). Gravel was also initially tested, but due to its limited performance, it was not included in further analyses.

However, it should be noted that one of the objectives of this study is to demonstrate that native materials can improve water mineral quality, through ensuring the recommended mineral concentrations in drinking water. Therefore, rather than attempting to validate a single group or type of material as a universal solution, the goal is to open the field of research to diverse alternatives of region-specific materials that may have potential for application in other contexts where atmospheric water production occurs under survival conditions.

5.3 Natural materials characterization

Soil, clay, beige sand, and red sand samples were analyzed by ICP-MS to determine their elemental composition. For interpretation purposes, samples were grouped as *soils* (soil and clay) and *sediments* (beige sand and red sand). The main objective was to establish an ion balance, particularly for target ions, by comparing the elemental composition of the native materials to the ions extracted during leaching. This approach helps assess the leaching capacity of each material and also identify the potential release of undesirable ions into the water (**Appendix B**).

Overall, all materials showed a significant presence of target ions, like calcium, which was predominant in most samples except for red sand, where magnesium was more abundant. Comparing these compositional data with the leaching results provides insight into how readily each material releases these essential ions. The findings suggest that clay and beige sand exhibit greater resistance or lower leaching efficiency for calcium and magnesium, despite their high content, compared to soil and red sand.

Heavy metals were also detected in the composition of the materials, raising concern due to their potential health risks if released into drinking water (**Table 5.2**). However, it is important to note that the analytical procedure used is an acid digestion, it involves extreme conditions that do not reflect natural environments or typical water contact scenarios. Studies have shown that water quality parameters such as salinity, dissolved oxygen, temperature, and pH significantly influence the solubility and mobility of heavy metals in drinking water. Therefore, a special control should be given to these variables when evaluating potential risks.

According to Surbakti et al. (2021) [146], heavy metals tend to accumulate in sediments at higher temperatures. In contrast, dissolved oxygen promotes their solubility in water, while its absence increases their retention in sediments. Elevated water salinity encourages the formation of organic matter aggregates, accelerating metal sedimentation and reducing their concentration in the water column. Additionally, controlled pH levels decrease metal solubility, leading to greater metal precipitation and settling. Supporting this, the literature indicates that a pH range of 6.5 to 8.0 is generally considered optimal for plant nutrition, as it allows for the availability of most essential nutrients while minimizing the mobility of harmful metals that could interfere with plant health.

Table 5.2. Hazardous heavy metals in drinking water (mg/L) and health implications [145]

Unwanted heavy metals in the water	Maximum contaminant level (mg/L)	Health implications in humans
Arsenic (As)	0.01	Vascular diseases, internal cancers, and skin issues
Cadmium (Cd)	0.003	Kidney problems, renal disease, and cancer-causing agent
Chromium (Cr)	0.05	cancer-causing agent, nausea, headache, vomiting, diarrhea
Copper (Cu)	2	Wilson's disorder, liver problems and insomnia
Nickel (Ni)	0.07	cancer-causing agent, coughing, chronic asthma, nausea, and dermatitis
Zinc (Zn)	3	Increased thirst, neurological symptoms, fatigue, depression
Lead (Pb)	0.01	Nervous system disease, cardiovascular issues, kidney disorders, and harm to the developing brain
Mercury (Hg)	0.006	Kidney problems, cardiovascular diseases, nervous system disorders, and rheumatoid arthritis

5.3.1 Soils

Overall, the materials showed the highest concentrations compared to the other elements (though in varying order) of aluminum, calcium, iron, and magnesium (**Figure 5.3**, **Figure 5.4**). These elements were present at concentrations above 10^3 mg/kg in soil and clay samples. Notably, the clay sample also contained a considerable amount of manganese, a metal associated with neurotoxicity, as well as operational and aesthetic issues in water systems when leached [100]. In contrast, the soil sample contained phosphorus peroxide and potassium oxide, two compounds commonly linked to agricultural activities, suggesting possible anthropogenic influence on the sample.

A study by Pučko et al., 2024 [108] investigated the elemental composition of topsoil and subsoil across Slovenia, revealing high variability within the same region. This variability is primarily attributed to geogenic processes and anthropogenic influences, which can alter soil composition and contribute to contamination. The average concentrations reported were approximately 30,000 mg/kg for iron, 20,300 mg/kg for aluminum, 9,650 mg/kg for calcium, and 6,700 mg/kg for magnesium. Additionally, the study provided 25th and 75th percentiles, as well as minimum and maximum values for these and other elements, highlighting the wide range of elemental concentrations present in soils.

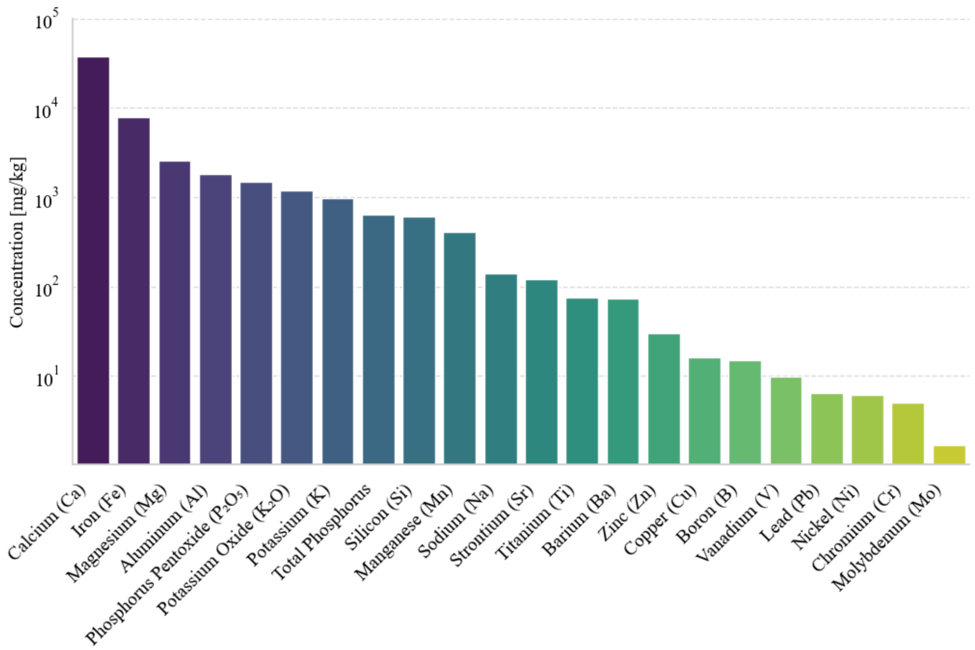

Figure 5.3. Elemental analysis of a soil sample by ICP-MS, expressed in mg/kg and presented on a log scale

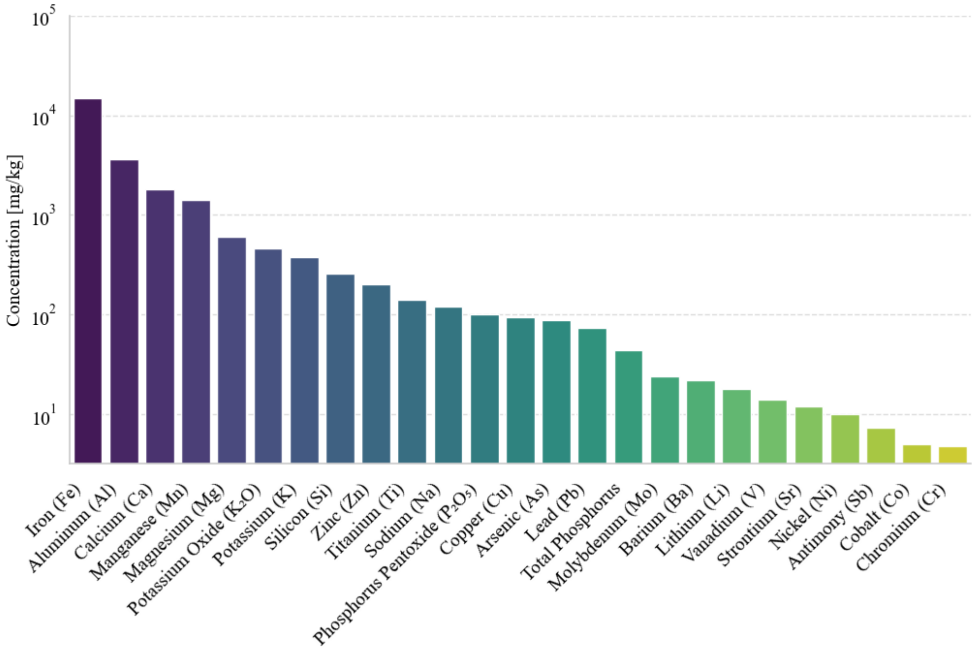

Figure 5.4. Elemental analysis of a clay sample by ICP-MS, expressed in mg/kg and presented on a log scale

5.3.2 Sediments

The highest concentrations in red sand and beige sand were observed for aluminum, iron, and magnesium (**Figure 5.5**, **Figure 5.6**). The red sand sample collected near a body of seawater on Prince Edward Island, showed a notable concentration of sodium. As discussed by Stowell, 1927, seawater contains high levels of Na^+ and Mg^{2+}, which compete for adsorption sites on sand particles [123]. This competition likely explains the lower calcium levels, as ion exchange processes favor the replacement of Ca^{2+} by Na^+ or Mg^{2+}, especially under slightly acidic pH, in the presence of chlorides, or high salinity. Sodium, being monovalent and smaller in size, more easily integrates into the mineral matrix.

The beige sand sample exhibited a high calcium content that was not reflected in leaching results, indicating that a dominant elemental presence in the solid matrix does not necessarily translate to higher ion release in water. Phosphorus pentoxide and potassium oxide were also detected in both red and beige sand, indicating anthropogenic influence as a possible reason for the introduction of additional ions and/or contaminants into the material.

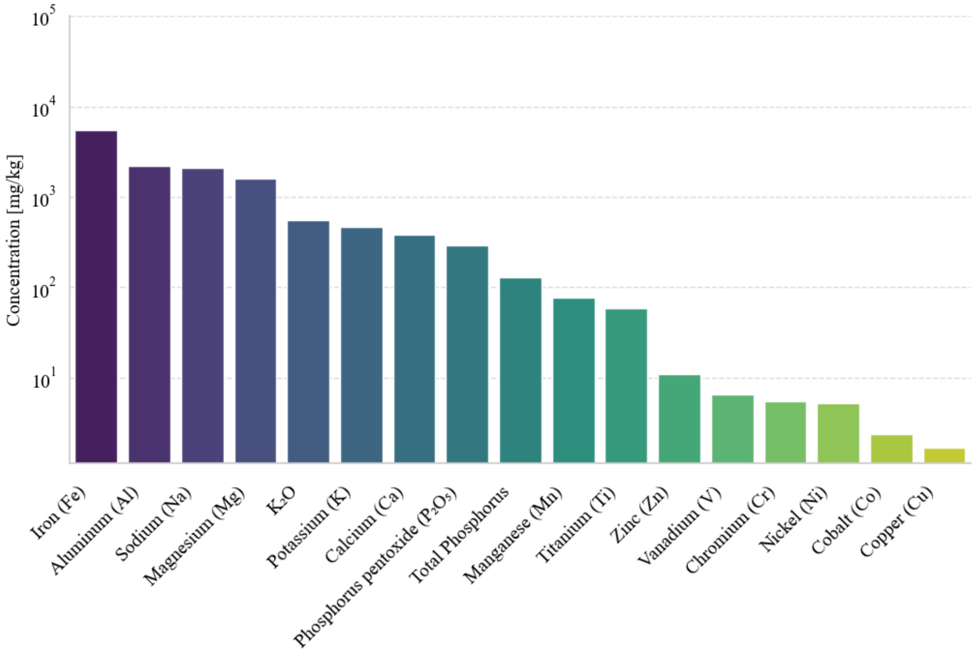

Figure 5.5. Elemental analysis of a red sand sample by ICP-MS, expressed in mg/kg and presented on a log scale

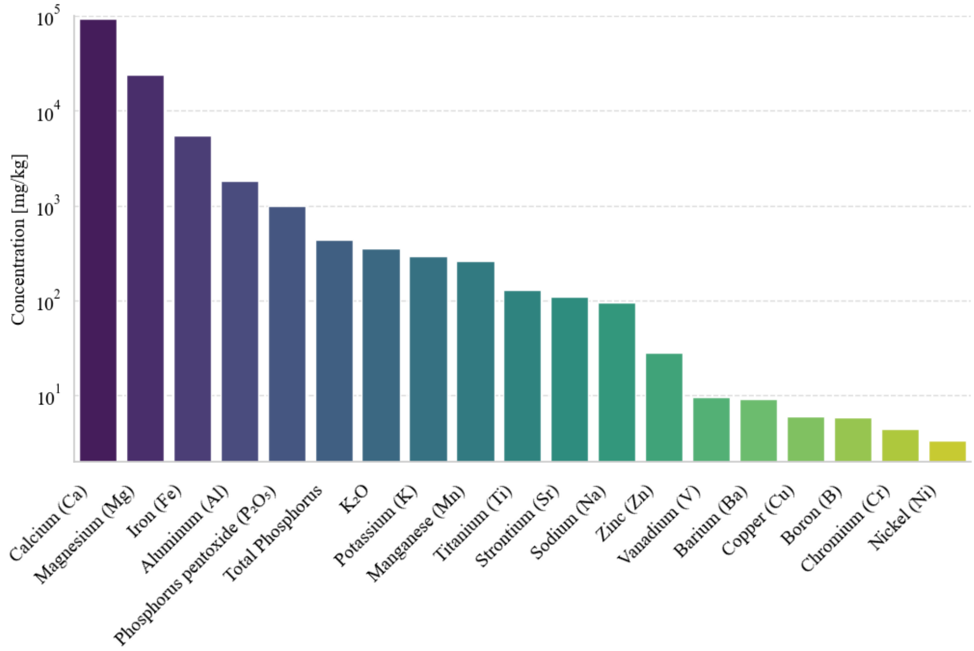

Figure 5.6 Elemental analysis of a beige sand sample by ICP-MS, expressed in mg/kg and presented on a log scale

5.4 Remineralization filter

Given the growing use of point-of-use (POU) technologies to treat drinking water at the household level, this study evaluated the performance of accessible, low-cost commercial mineralizing filters. Their effectiveness in mineralizing deionized water was previously demonstrated (**Figure 4.3**). However, the current focus was to assess their ion contribution when used with tap water from the city of Montreal, under more practical conditions (**Figure 5.7**)

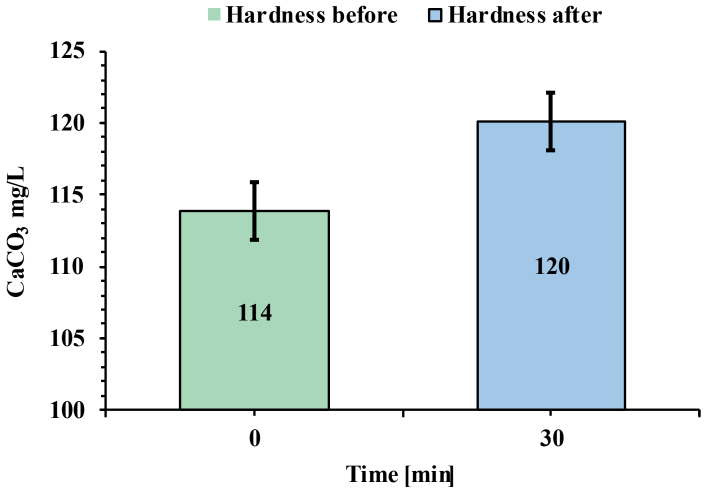

Figure 5.7. Results of hardness for the tap water, before and after contact with mineralization filter.

The results did not show the expected improvements as suggested by vendors, which claim enhancements such as improved taste and increased ion concentrations, up to 20.8 mg/L of calcium (52 mg/L as $CaCO_3$), 32.7 mg/L of sodium (71.1 mg/L as $CaCO_3$), and 4 mg/L of potassium (5.1 mg/L as $CaCO_3$).

Consumer opinions on water quality improvement were highly variable, with no consensus on effectiveness [168]. A study on commercial mineralizing filters notes that these products are often surrounded by marketing myths. Specifically, the authors found no scientific evidence supporting the claimed benefits, suggesting that these affirmations are largely driven by marketing narratives [169].

The composition of this filter is typically undisclosed, prompting an internal inspection (**Figure 5.8**). Upon opening, the filter was found to contain a charcoal-based structure mixed with white particles, potentially representing the ion exchange agent. SEM imaging could be useful to analyze these particles. The author suggests the presence of calcite integrated into the matrix as the possible mineralizing agent.

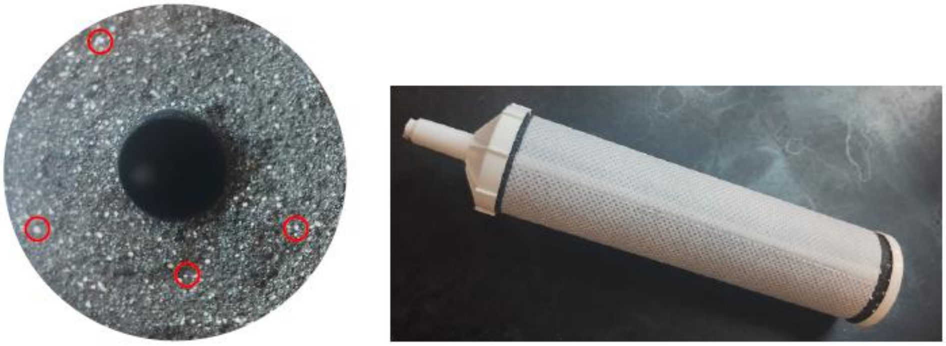

Figure 5.8. Inside view of mineralization filter.

CHAPTER 6 CONCLUSION AND RECOMMENDATIONS

This project represents an effort to ensure access to quality water in communities with limited resources under survival conditions. The project proposes to improve atmospheric water harvesting (AWH) water by enriching it with essential minerals such as calcium and magnesium through mineral dissolution from natural materials. Among the natural materials evaluated, soil (0.03 g/mL) and red sand (0.25 g/mL) showed high potential for adjusting water hardness, reaching concentrations of 182 mg/L and 265 mg/L $CaCO_3$, respectively. Furthermore, rapid ion release kinetics were observed, with saturation levels occurring after only 15 minutes of contact, suggesting good performance in cyclic processes, in the case of soil, it can be extrapolated that after five cycles, water hardness will reach the recommended health range; beyond this point, ion release is expected to decline. These results aim to advance the viability of sorbent-based AWH systems to produce water that is not only accessible, but also suitable for human consumption, meeting basic physico-chemical quality parameters. Overall, this approach reaffirms the value of water as a vital resource and strengthens the possibility of considering low-consumable mineralization systems for decentralised production of atmospheric water in contexts of need.

The main recommendations of the study are listed below:

- Conduct exploratory testing by modifying soil and sand proportions, evaluating their combined effects, as well as other types of native materials. Investigate various particle size distributions and their influence on ion exchange capacity or mineralization capacity.
- Analyze the effects of different heat pre-treatment conditions on soil properties.
- Combine materials strategically and model the performance of filtering media to estimate process robustness, operational capacity, and material lifespan.
- Use packed-bed contactors for scale-up studies in continuous modes. Monitor permeability loss and porosity reduction, and mineral release decline over time to evaluate long-term performance and estimate system lifetime.
- An additional factor to consider during scale-up is the hydraulic permeability coefficient, which reflects the influence of native material porosity when used in packed beds. This parameter, along with tortuosity, helps evaluate the optimal flow paths through the material, ensuring maximum contact between the water and the surfaces of mineralizing materials.

- Simulate reaction pathways in continuous systems using native resources.
- Conduct tests with actual water collected directly from the atmosphere to identify potential discrepancies between laboratory results and real-world applications.
- Implement microbiological testing (e.g., heterotrophic plate counts - HPC) to ensure water safety across scenarios.
- Adjust filtration size to improve dissolved organic carbon (DOC) levels.
- Develop a standardized mineralization protocol for non-conventional water sources.
- Encourage regulatory frameworks that acknowledge the health benefits of mineral ions in drinking water and define optimal levels based on regional dietary needs.

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APPENDIX A – SUPPLEMENTARY INFORMATION OF THE ARTICLE

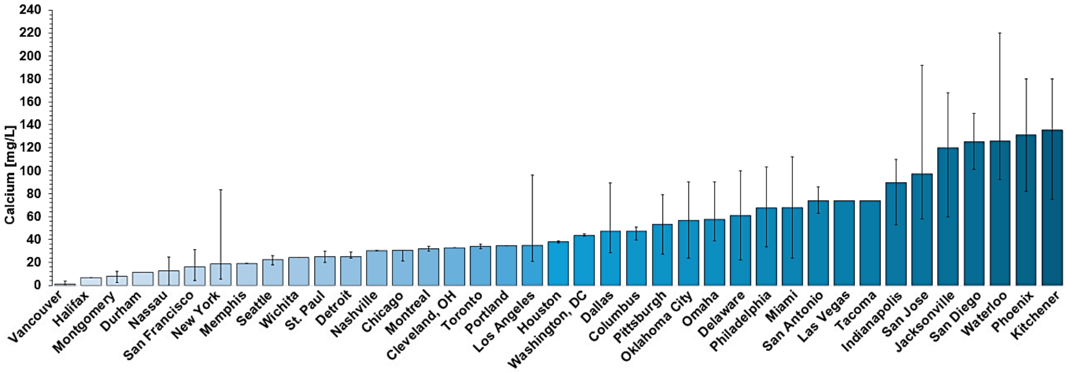

Figure A.1. Calcium Levels in some major U.S. and Canadian Tap Water alcium Levels [141]

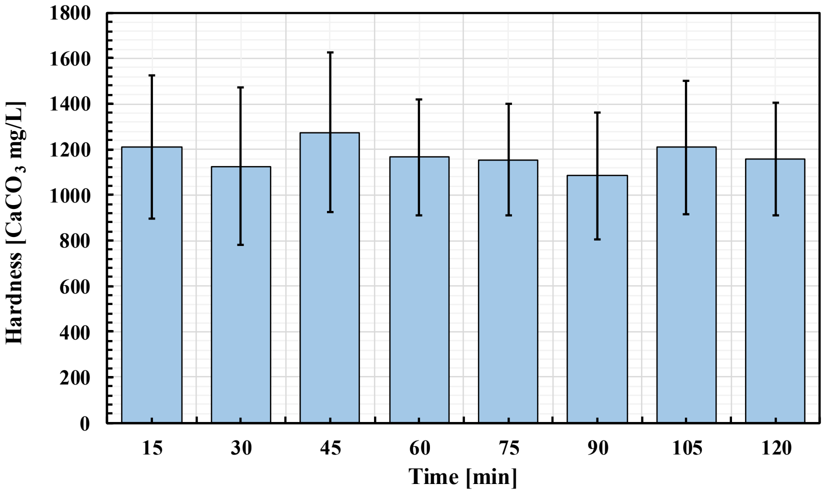

Figure A.2. Hardness of water samples exposed to a soil ratio of 0.25g/mL for extended contact times (25 g / 100 mL, 200 rpm stirring, n=3)

Baseline water quality parameters table data

Note that many are non-regulatory parameters reported in the literature for drinking water, data may vary from area to area and must be adapted for the area where no conventional water sources remineralization is deployed.

Table A.1. Baselines for water quality

Parameter	Drinking water expected value	Reference
pH	7.0 – 10.5	[151]
Dissolved Organic Carbon (DOC)	≤ 2 mg/L	[153]
Conductivity	100 - 500 µS/cm	[170]
Turbidity	≤ 5 NTU	[148]
UV-Vis at 254 nm	0.1 - 0.3 abs	[149,150]
Dissolved Solids (TDS)	200 - 500 mg/L	[24]
Water Hardness as mg CaCO3/L	182 – 364	[140]

Results of the water quality parameters

As well, seven water quality analyses were performed after the samples had been in contact with the mineralizing materials for 15 min. Table S.2. summarizes the results, including hardness, dissolved solids, and measurements of pH, DOC, conductivity, turbidity, and UV-Vis absorbance at 254 nm.

Table A.2. Results of the different water samples after contact with mineralizing materials

Parameter	**Units**	**Ultrapure Water**	**Soil**	**Soil**	**Red Sand**	**Beige Sand**	**Clay**	**Corosex™**	**Calcite**
Ratio	g/mL	0	0.03	0.25	0.25	0.25	0.25	0.25	0.25
Contact time	min	0	15	15	15	15	15	15	15
Hardness	$CaCO_3$ mg/L	0.23	182.2	875.8	265.0	30.2	12.7	142.90	30.60
pH	-	5.85	5.85	5.31	6.66	9.32	8.50	11.23	8.39
DOC	C mg/L	0.21	183.5	1170	20.1	1.33	0.43	-	-
Conductivity	µS/cm	0.8	356.2	1213.1	2902.3	56.5	49.3	469.0	74.7
Non-filtered Turbidity	NTU	0.09	71.5	>4000	1077	>4000	1380	1083	1106
Filtered Turbidity	NTU	0.09	5.50	12.6	41.4	109	83.2	0.14	0.53
UV-VIS 254 nm	Abs/cm	0.06	0.52	0.61	0.36	0.08	0.12	0.07	0.18
Dissolved Solids	mg/L	0	703	2875	3206	100	52	134	6

Granulometric analysis and physical-structural properties of native materials

Table A.3. Comparison of granulometric analysis between fine materials: soil, red sand and beige sand (< 2000 µm)

<table>
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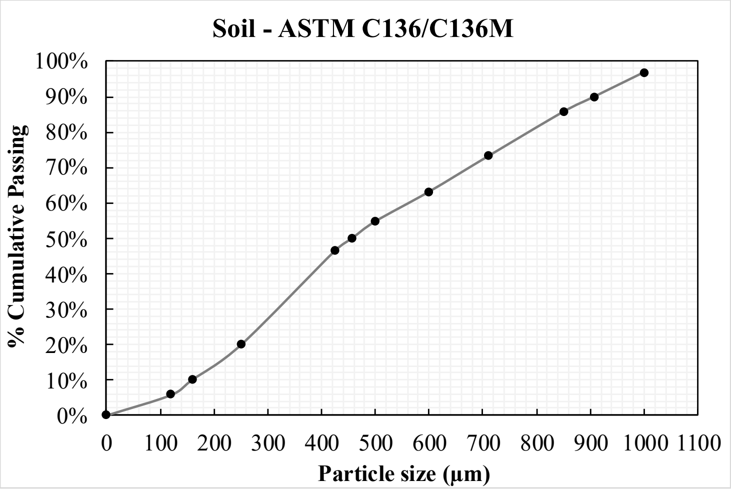
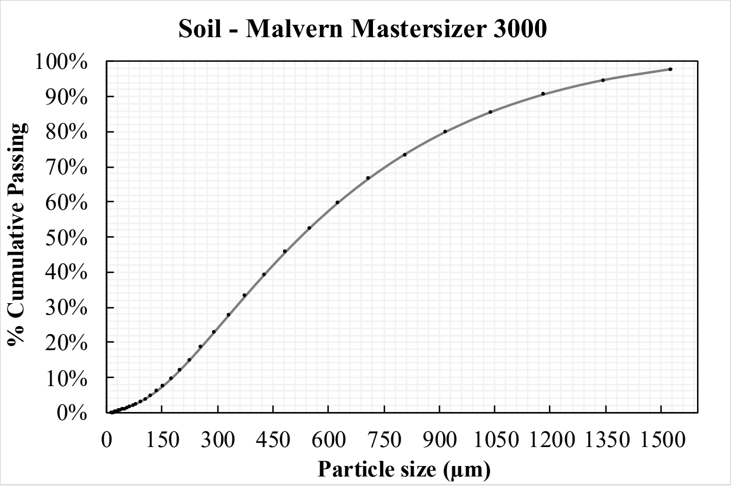
<tr><td>
</td><td>
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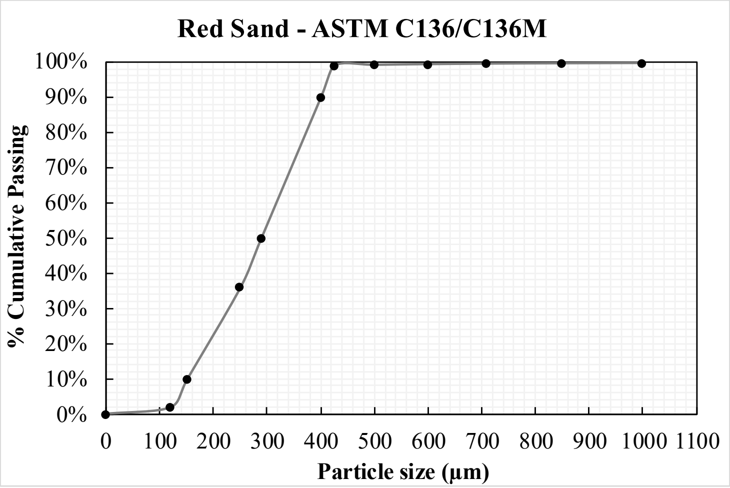
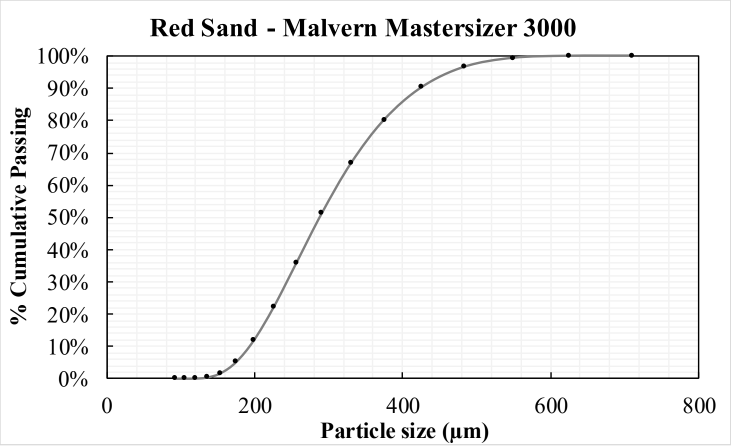
<tr><td>
</td><td>
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Table A.3 (cont'd). Comparison of granulometric analysis between fine materials: soil, red sand and beige sand (< 2000 μm)

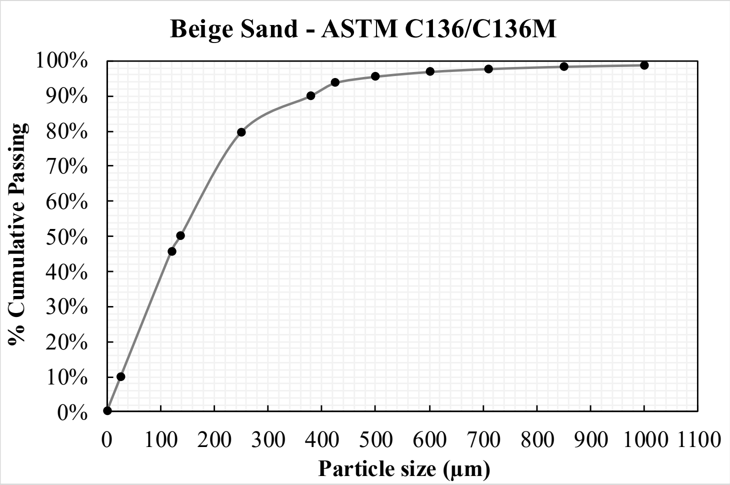
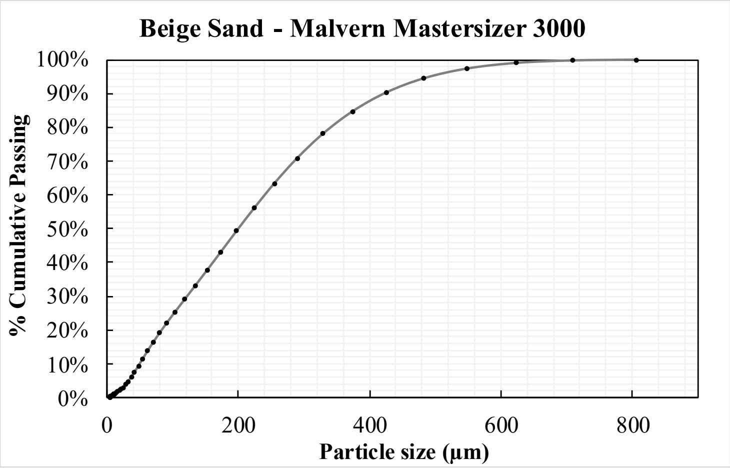
	

Table A.4. Comparison of granulometric analysis between coarse materials: gravel and clay pebbles (≥ 2000 μm)

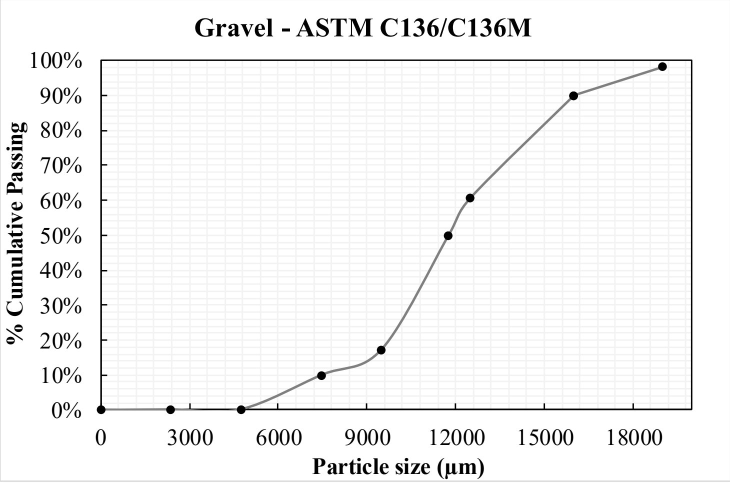
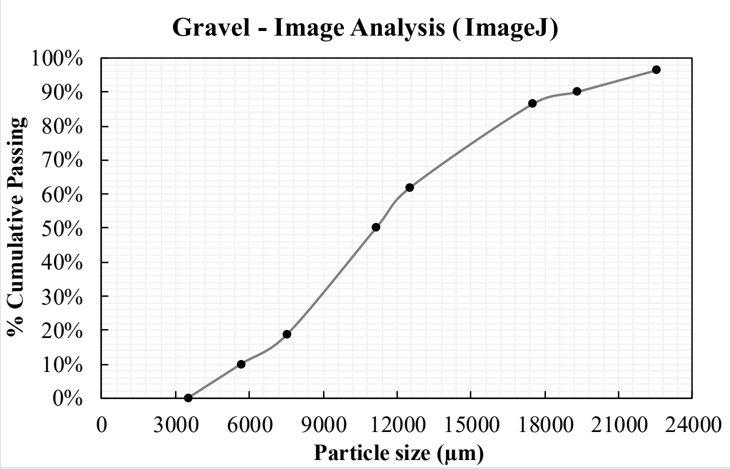
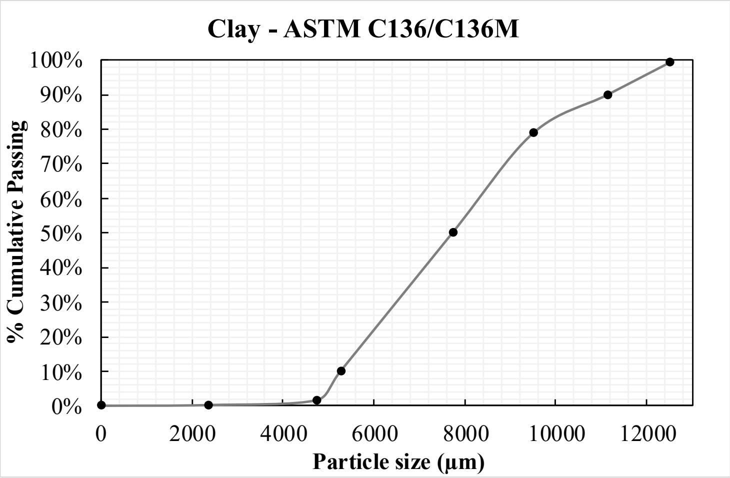
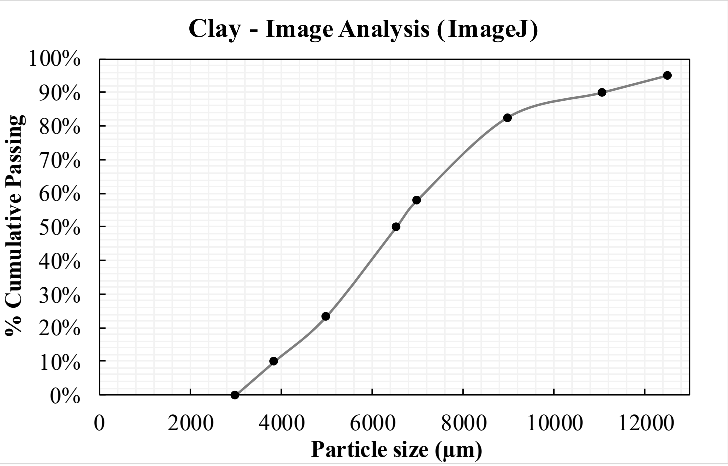
Method: ASTM C136/C136M	**Method: ImageJ software**
	

Table A.4 (cont'd). Comparison of granulometric analysis between coarse materials: gravel and clay pebbles (≥ 2000 µm)

APPENDIX B – ICP MS RESULTS

Table B.1. ICP – MS RESULTS FOR THE SOILS

Metals	Unit	Sample Soil	Sample Clay	LDR
Aluminum (Al)	mg/kg	1800	3600	20
Antimony (Sb)	mg/kg	<2.0	7.4	2
Silver (Ag)	mg/kg	<0.50	<0.50	0.5
Arsenic (As)	mg/kg	<5.0	88	5
Barium (Ba)	mg/kg	74	22	5
Beryllium (Be)	mg/kg	<0.50	<0.50	0.5
Bismuth (Bi)	mg/kg	<7.0	<7.0	7
Boron (B)	mg/kg	15	<5.0	5
Cadmium (Cd)	mg/kg	<0.50	<0.50	0.5
Calcium (Ca)	mg/kg	38000	1800	30
Chromium (Cr)	mg/kg	5	4.8	2
Cobalt (Co)	mg/kg	<2.0	5	2
Copper (Cu)	mg/kg	16	94	2
Tin (Sn)	mg/kg	<4.0	<4.0	4
Iron (Fe)	mg/kg	7800	15000	10
Potassium Oxide (K_2O)	mg/kg	1200	460	50
Lithium (Li)	mg/kg	<10	18	10
Magnesium (Mg)	mg/kg	2600	610	10
Manganese (Mn)	mg/kg	410	1400	2

Table B.1 (cont'd). ICP – MS RESULTS FOR THE SOILS

Mercury (Hg)	mg/kg	<0.067	<0.020	0.02
Molybdenum (Mo)	mg/kg	1.7	24	1
Nickel (Ni)	mg/kg	6.2	10	1
Phosphorus Pentoxide (P_2O_5)	mg/kg	1500	100	50
Total Phosphorus	mg/kg	640	44	20
Lead (Pb)	mg/kg	6.5	73	5
Potassium (K)	mg/kg	980	380	40
Selenium (Se)	mg/kg	<1.0	<1.0	1
Silicon (Si)	mg/kg	610	260	10
Sodium (Na)	mg/kg	140	120	40
Strontium (Sr)	mg/kg	120	12	10
Tellurium (Te)	mg/kg	<20	<20	20
Thallium (Tl)	mg/kg	<2.0	<2.0	2
Thorium (Th)	mg/kg	<4.0	<4.0	4
Titanium (Ti)	mg/kg	76	140	5
Tungsten (W)	mg/kg	<5.0	<5.0	5
Uranium (U)	mg/kg	<5.0	<5.0	5
Vanadium (V)	mg/kg	9.9	14	5
Zinc (Zn)	mg/kg	30	200	10
Zirconium (Zr)	mg/kg	<5.0	<5.0	5

Table B.2. Metals below the limit detection range for the soil sample

Metals Below LDR (Sample Soil)	**(Sb)**	**(Ag)**	**(As)**	**(Be)**	**(Bi)**	**(Cd)**	**(Co)**	**(Sn)**	**(Li)**	**(Hg)**	**(Se)**	**(Te)**	**(Tl)**	**(Th)**	**(W)**	**(U)**	**(Zr)**

Table B.3. Metals below the limit detection range for the clay sample

Metals Below LDR (Sample Clay)	(Ag)	(Be)	(Bi)	(B)	(Cd)	(Sn)	(Hg)	(Se)	(Te)	(Tl)	(Th)	(W)	(U)	(Zr)

Table B.4. ICP – MS RESULTS FOR THE SEDIMENTS

Metals	**Unit**	**Sample Beige Sand**	**Sample Red Sand**	**LDR**
Phosphorus pentoxide (P_2O_5)	mg/kg	1000	290	50
Aluminum (Al)	mg/kg	1800	2200	20
Antimony (Sb)	mg/kg	<2.0	<2.0	2
Silver (Ag)	mg/kg	<2.0	<2.0	2

Table B.4 (cont'd). ICP – MS RESULTS FOR THE SEDIMENTS

Arsenic (As)	mg/kg	<2.0	<2.0	2
Barium (Ba)	mg/kg	9.1	<5.0	5
Beryllium (Be)	mg/kg	<0.50	<0.50	0.5
Bismuth (Bi)	mg/kg	<5.0	<5.0	5
Boron (B)	mg/kg	5.8	<5.0	5
Cadmium (Cd)	mg/kg	<0.10	<0.10	0.1
Calcium (Ca)	mg/kg	93000	380	30
Chromium (Cr)	mg/kg	4.4	5.5	2
Copper (Cu)	mg/kg	5.9	1.7	1
Cobalt (Co)	mg/kg	<2.0	2.4	2
Tin (Sn)	mg/kg	<5.0	<5.0	5
Iron (Fe)	mg/kg	5500	5500	10
K_2O	mg/kg	350	550	65
Lithium (Li)	mg/kg	<10	<10	10
Magnesium (Mg)	mg/kg	24000	1600	10
Manganese (Mn)	mg/kg	260	76	2

Table B.4 (cont'd). ICP – MS RESULTS FOR THE SEDIMENTS

Molybdenum (Mo)	mg/kg	<2.0	<2.0	2
Nickel (Ni)	mg/kg	3.3	5.2	1
Mercury (Hg)	mg/kg	<0.050	<0.050	0.05
Total Phosphorus	mg/kg	440	130	20
Potassium (K)	mg/kg	290	460	50
Lead (Pb)	mg/kg	<5.0	<5.0	5
Selenium (Se)	mg/kg	<1.0	<1.0	1
Sodium (Na)	mg/kg	95	2100	10
Strontium (Sr)	mg/kg	110	<10	10
Tellurium (Te)	mg/kg	<20	<20	20
Thallium (Tl)	mg/kg	<2.0	<2.0	2
Thorium (Th)	mg/kg	<5.0	<5.0	5
Titanium (Ti)	mg/kg	130	58	5
Tungsten (W)	mg/kg	<5.0	<5.0	5
Uranium (U)	mg/kg	<5.0	<5.0	5
Vanadium (V)	mg/kg	9.6	6.5	5

Table B.4 (cont'd). ICP – MS RESULTS FOR THE SEDIMENTS

Zinc (Zn)	mg/kg	28	11	5
Zirconium (Zr)	mg/kg	<5.0	<5.0	5

Table B.5. Metals below the limit detection range for the beige sand sample

Metals Below LDR (Sample Beige Sand)	(Sb)	(Ag)	(As)	(Be)	(Bi)	(Cd)	(Co)	(Sn)	(Li)	(Mo)	(Hg)	(Pb)	(Se)	(Te)	(Tl)	(Th)	(W)	(U)	(Zr)

Table B.6. Metals below the limit detection range for the red sand sample

Metals Below LDR (Sample Red Sand)	(Sb)	(Ag)	(As)	(Ba)	(Be)	(Bi)	(B)	(Cd)	(Sn)	(Li)	(Mo)	(Hg)	(Pb)	(Se)	(Sr)	(Te)	(Tl)	(Th)	(W)	(U)	(Zr)