An assessment of technological development and applications of decentralized water reuse: a critical review and conceptual framework

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OVERVIEW

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An assessment of technological development and applications of decentralized water reuse: A critical review and conceptual framework

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Abstract

Rapid development, urbanization, and population growth have contributed to water stress in many parts of the world. As freshwater sources are finite, it is essential to source for alternatives to ensure water security. Reclamation of non-conventional water sources (i.e., rainwater and greywater) can be a viable alternative to alleviate water stress. In this work, various laboratory, pre-commercialization scale, and commercialized products for rainwater harvesting and greywater treatment and reuse were reviewed. As a result, a conceptual framework is proposed to provide an overview on the applicability of technologies under various settings, which were mapped against the intended use of treated water and the potential for water supply expansion. This conceptual framework could aid decision makers in deciding on a suitable decentralized solution for water reclamation depending on limiting criteria. Decentralized systems of rainwater harvesting and greywater treatment for reuse are going to be crucial in reducing the dependence on the centralized water supply.

This article is categorized under:

Engineering Water > Planning Water

Water and Life > Conservation, Management, and Awareness

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KEYWORDS
decentralized, greywater, rainwater, urban, water reuse

1 | INTRODUCTION

The world's main water sources consist of both saltwater and freshwater. Salt water contributes 97.5% of the world's water. Meanwhile, freshwater is made up of groundwater and surface water, merely 2.5% of the world's water (UNESCO World Water Assessment Programme [UNESCO WWAP], 2020). Freshwater withdrawals are used for agricultural, industrial, or domestic uses. Numerically, there is sufficient volume of freshwater for everyone on Earth. However, irregular water distribution, wastage, pollution, and poor water management add to the ever-increasing water tension. Furthermore, population growth, rapid urbanization, and industrialization with increasing irrigated agriculture to meet the demand of staple food production contributed to increasing water demand. The current population of 7.7 billion people is projected to grow by 26% in 2050 (UN, Department of Economic and Social Affairs, Population Division, 2019). In the last century, water consumption has escalated at more than twice the rate of population growth (UN, 2021). By 2030, it is estimated water scarcity could displace 700 million people (UN, 2020). This situation is compounded by two factors: water pollution and climate change.

Almost 2.3 billion people currently live in high water stress facing countries (UN-Water, 2021). The majority of these countries from Sub-Saharan African, Asia, and Oceania suffer from either physical water scarcity or economical water scarcity reflected in the categories of high to extremely high stress zones. Physical scarcity happens when there is insufficient water to meet demands, whereas economic scarcity occurs when there is lack of investment in water due mainly to water poverty. The SDG report of the UN-Water (2021) reveals that Western Asia and Northern Africa and Central and Southern Asia are withdrawing more than 70% of available water resources. The water scarcity problem can be addressed through various pragmatic ways such as water allocation to a variety of uses, reform of water management, changes in water policy, and appropriate investments in order to ensure sustainability in water use. Innovative strategies have been elucidated to address challenges associated with water scarcity, which include increased funding in water-use efficiency, wastewater treatment, reuse, and protection of water ecosystems (UN-Water, 2021). For example, water-use efficiency has increased by 9% globally since 2015 (UN-Water, 2021). Some strategic efforts to mobilize the water-use efficiency plan include water pricing policy, adding water meters to make consumers reduce their water usage, encouraging the use of household water efficient and water reuse appliances and fittings, to name a few.

One of the most efficient adaptation strategies for water supply and demand management is to use non-traditional water resources for water supply such as rainwater harvesting, greywater recycling, and reuse. This is further supported by the fact that a high percentage of the consumed water worldwide is not treated, and the abundantly available annual precipitation is not tapped effectively. This situation must change due to the limited supply of safe water currently available, thus water reclamation is a progressive measure. This is in tandem with Target 6.3 of SDG 6 which addressed the need to halve the proportion of untreated wastewater and substantially increase recycling and safe reuse globally. One of the indicators for achieving this target is to safely treat the proportion of domestic and industrial wastewater flow. There are various technologies for water reclamation and reuse throughout the world, especially centralized systems that follow existing international, national, and local guidelines and regulations. However, recent advancement in water recycling technologies such as decentralized systems and green technology together with the emergence of complicated situations due to urbanization like heavy pollution of freshwater sources and an increasing number of informal settlements in huge metropolitan cities, shift the research priorities toward the need to review the technological development and applications of water reuse to update water reclamation guidelines for small-scale technologies and form a conceptual framework for proper applications in urban areas (Angelakis et al., 2018; Reynaert et al., 2021).

Development of decentralized water recycling and reuse, especially in developing countries facing physical and economical water scarcity, could be a sustainable solution to provide safe, acceptable, and affordable water to people from these localities. However, when deciding an appropriate system for implementation, many factors need to be considered such as the availability of technology, location of implementation, and possibility of expansion. At present, there are limited sources of work that have reviewed the technological advancement for decentralized water recycling systems and used the conceptual framework to assess the applications of these technologies in different situations. Therefore, this article aims to review domestic water recycling and safe reuse globally with a particular focus on rainwater and greywater technologies together with the assimilation of water efficiency technological development in a conceptual framework for urban scale water reuse. The review presents crucial evidence for the scientific community and the stakeholders for adopting and developing water-reuse related strategies.

2 | WATER RESOURCES AND CONSUMPTIONS

2.1 | Traditional water sources

Freshwater is made up of surface water, groundwater, glacier, and permafrost (UNESCO WWAP, 2020). Freshwater is the traditional main source of potable water. Potable water which is synonymous to drinking water is used in daily life for various reasons in different countries including drinking, cooking, basic hygiene, sanitation, garden watering, in addition to recreational, agricultural, and industrial activities.

In developed countries such as the United States and the United Kingdom, on average 68% of community water system users receive water from surface water, while the rest receive it from groundwater (U.S. Department of Health & Human Services, 2009; Water UK, 2020). However, most of the tap water used in Australia comes from rainwater. Rainwater tanks are widely used to collect drinking water for rural areas in Australia (Environmental Health, 2020). The use of the rapid, low-cost provision of good quality groundwater as a potable water source is more evident in developing countries or rural areas of developed countries across colossal areas of Asia, Africa, and Latin America (Carrard et al., 2019; Foster et al., 2000). For example, Southeast Asia reported high rates of rural household groundwater consumption including Indonesia (90%), Timor-Leste (81%), and Myanmar (78%) (Carrard et al., 2019). In India, surface water and groundwater are utilized at around 690 and 396 km^3, respectively, annually (Kumar et al., 2005). It is estimated that 75% of the African population uses groundwater as the main source of drinking water (UN Water/Africa, 2004). Despite having river basins covering 64% of the continent's land area in Africa, only 22%–34% of the population have access to safe water in at least eight Sub-Saharan countries and in 2015, the population without access to potable water increased to almost half of global population (Ritchie & Roser, 2021a; Tatlock, 2006). The main reasons for this are insufficient infrastructure to mobilize the water source and transboundary conflicts (Musingafi, 2013). There is causality between economic development and water accessibility, chiefly from investment in water resources perspective (Doungmanee, 2016).

Water withdrawals are defined as the permanent or temporary removal of freshwater from surface or groundwater sources to be channeled for purposes such as domestic supply, agriculture, and industries (Ritchie & Roser, 2017). While the benefit of the groundwater outlined above, over-abstraction of groundwater through drilling, and pumping has negative impacts on hydrogeology (Carrard et al., 2019). Excessive abstraction of groundwater will exhaust the aquifer over time and consequently disturb the hydraulic balance (Gun, 2021). This can also allow the intrusion of natural underground contaminants (arsenic), low-quality surface water, seawater or even sewage leach from nearby areas, reducing the quality of groundwater, and causing health effects (Gun, 2021). On the other hand, in many other places, surface water is commonly withdrawn for supply due to its easy accessibility. In some cases, river water can be collected by building dams and funneled to treatment plants via a pipeline network. Dams are also built for other purposes than water supply such as flood control and, hydropower generation. Despite multiple benefits of having dams, they can have negative environmental, social, and ecological impacts. Forced resettlement is faced by many vulnerable communities, mainly indigenous communities who have a special bond with nature. For example, about 10,000 local people along the Bakui River in Borneo, Malaysia were relocated to a place 40 km downstream their customary land due to the construction of Bakun Dam, the largest dam in Southeast Asia (Aiken & Leigh, 2015; Cooke et al., 2017). They were also affected by the lack of social impact assessment of the megaproject development (Cooke et al., 2017). The project also destroyed the ecosystem by denuding the forest and disturbing fish migration (Aiken & Leigh, 2015). There is a strong need for governments and developers to mitigate the environmental and social effects of functioning dams. They need to critically evaluate the advantages and disadvantages of the construction of large dams for water withdrawals.

The current water withdrawal is escalating at a rate about 1% annually and the global water demand is estimated to increase by 20%–30% by 2050 (UNESCO, 2021). The water withdrawal pattern of each country is strongly dependent on its socioeconomic construction. Agriculture contributes to 70% of freshwater withdrawal globally (Ritchie & Roser, 2017). In 2010, India was the largest agricultural water consumer, at nearly 688 billion m^3, followed by China at 388 billion m^3, and the United States at about 175 billion m^3 (Ritchie & Roser, 2017). Agriculture, for many developing countries, contributes a smaller share of income compared with other sectors; however, consumes the largest proportion of water, where more than 90% water resources of developing countries are allotted to agriculture (Doungmanee, 2016; UNESCO WWAP, 2017). For industrial water uses, the United States is the biggest consumer at nearly 250 billion m^3, almost double that of China (Ritchie & Roser, 2017). In general, it can be observed that countries across Europe, Americas, Pacific, and East Asia consume more than a billion m^3 annually and the rates for Sub-Saharan Africa and South Asia reported at the low side accounting an average volume of 500 million m^3 (Ritchie & Roser, 2017). For higher-income countries, the industrial sector forms a bigger share of total gross domestic product and provides a larger allotment of employment, and thus, contributing to a higher industrial water withdrawal share. In terms of municipal water withdrawal, China with the highest population number dominated the chart, followed by the United States and India (Ritchie & Roser, 2017). Even though the United States had an almost four times smaller population than India, it had higher domestic water consumption per capita. In many nations, especially in developing countries, population growth and urbanization intensify the pressure on many water resources, causing rapid depletion of supply (Ahuja, 2019). In general, while the strategy of investing in water infrastructure to expand the network water supply by tapping freshwater sources is necessary to bring on modernization and upgradation of water delivery systems (Peter-Varbanets et al., 2009; Rosegrant et al., 2002), improving the efficiency of water use is the most cost-effective and immediate way to conserve water for water sustainability.

2.2 | Reclamation of non-conventional water sources

Meeting growing demand by developing new water supplies has only limited potential and focus is increasingly being placed on exploring non-conventional water sources. Figure 1 illustrates the non-drinking water sources available from a dwelling compound which include greywater, blackwater, groundwater, and rainwater. Greywater originates from the bathroom sinks, showers, and washing machines, while blackwater comes from toilets and kitchen sinks. Blackwater is often composed of high nutrient-load and pathogens from fecal matter and food waste, in addition to oil-waste from cooking. These microbes are disease-causing. In contrast, greywater contains 80% less organic matter, suspended solid, and nutrient-load than blackwater (Hocaoglu et al., 2010). Blackwater together with greywater constitute the domestic wastewater. Even though many countries recycle wastewater for non-potable uses, there are few countries including Singapore, Australia, Namibia and few states like California, Virginia, and New Mexico that produce drinking water from reclaimed wastewater (Leong & Lebel, 2020). Recycling of domestic wastewater is more stringent due to inherent contaminants and the concept of "toilet-to-tap" is a psychological barrier among consumers. Rainwater is another readily available water source with minimal treatment required as it is free from natural contaminants. On the other hand, desalination is the process of recycling abundantly available salt water. However, the process of salt water reclamation is very costly and requires use of large areas of land compared with other reclaimed water

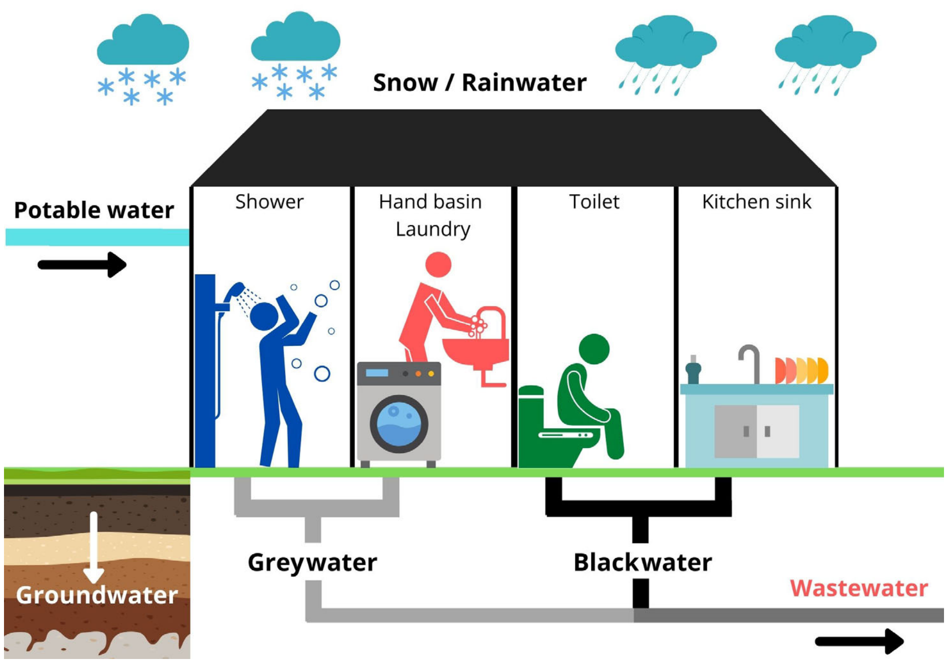

FIGURE 1 Schematic representation of non-drinking water sources available from a house compound which include greywater, blackwater, groundwater, and precipitations

(Hinkebein, 2004). Recycled water that is not subjected to the same processing restriction as drinking water can be used as a non-drinking water system for many purposes such as watering plants, flushing toilets, or washing house porches or cars. This will help in reducing the consumption of potable water from freshwater for non-potable usage. Rainwater harvesting and greywater recycling are the easily adaptable strategies for safe water reuse due to inherent low level of water contamination, lower cost, and land required depending on the system design (Boano et al., 2020; Oh et al., 2018). Even though these innovations are gaining popularity, their implementation is limited due to regional differences such as water price, availability, and technological accessibility (Peter-Varbanets et al., 2009).

2.2.1 | Characteristics of rainwater and greywater

The quality of rainwater and greywater can be measured by physical, chemical, and microbiological properties. Physical parameters are turbidity, total suspended solids (TSS), and total dissolved solids (TDS), whereas the chemical parameters are biological oxygen demand (BOD), chemical oxygen demand (COD), nitrates, phosphates, total nitrogen (TN), total phosphorus (TP), hardness, and heavy metals. Enumeration of total coliform, fecal coliform, and *Escherichia coli* (*E. coli*) are examples of microbiological quality standards. Rainwater in general is free from inherent impurities. However, composition of rainwater collected is heavily affected by different catchment areas. Rainwater collected from land run-offs is generally more polluted than rooftop as reflected by the higher values of TSS, TDS, COD, and bacterial enumeration; and atmospheric rainwater is the least polluted (Table 1). Level of heavy metals leached into collected

TABLE 1 Physical, chemical and biological properties of rainwater at different catchment areas

Rainwater quality parameters	Catchment areas		
	Atmospheric	Rooftop with different coating materials	Storm water
pH	4.4–8.7	4.6–8.1	6.4–8.3
Electrical conductivity (dS/m)	0.0038–0.0448	0.43–2.5	2.65
Alkalinity (mg/L)	4–43	54–150	132–651
Hardness (mg/L)	0–71	5–88	30–1305
Turbidity (NTU)	—	0.1–22.3	1.4–47.6
TSS (mg/L)	4–211	20–460	40–866
TDS (mg/L)	23–114	26–404	87–1693
Nitrates (mg/L)	0.018–3.60	0.1–17.0	4–120
Phosphates (mg/L)	0.01–0.04	0.03–0.5	0.1–4.03
Lead (mg/L)	0–0.004	0.001–0.01	0.028
Iron (mg/L)	0–0.008	0–0.19	0.038–4.96
Zinc (mg/L)	0.0012–0.02	0.03–1.46	0.085
COD (mg/L)	—	23–43	33–279
Fecal coliform (MPN[a] or CFU[b]/100 ml)	0[b]	3[a]	11[a]
E. coli (MPN[a] or CFU[b]/100 ml)	0[b]	2[a]	5–507[a]
References	Radaideh et al. (2009); Samuel et al. (2012); Chukwuma et al. (2013); Abulude et al. (2018); Liyandeniya et al. (2020)	Radaideh et al. (2009); Samuel et al. (2012); Lee et al. (2017); Khayan et al. (2019); Abuelfutouh et al. (2020)	Radaideh et al. (2009); McCarthy et al. (2012); Kayhanian et al. (2012); Samuel et al. (2012); Salehi et al. (2020)

Abbreviations: COD, chemical oxygen demand; TDS, total dissolved solids; TSS, total suspended solids.
[a]Indicates value for MPN.
[b]Refers to CFU.

TABLE 2 Physical, chemical, and biological properties of greywater globally

Greywater quality parameters	Countries					
	Americas	Oceania	Europe	Middle-East	Asia	Africa
Turbidity (NTU or +FTU)	34–100	—	93+	15–58	196–225	270
TSS (mg/L)	19–156	0.5–795	11–319	45–155	55–619	180–537
Nitrates (mg/L)	0.11	—	—	0.70	1.49–40	4.26–8.43
TN (mg/L)	4.3–50.3	—	0.5–15.0	10.6–24.1	29.7–41.2	17
TP (mg/L)	0.5–5.3	—	0.1–187	1.4–12	1.0–5	2.3–61
BOD (mg/L)	45–144	3–380	208–1363	335–568	5–445	204–350
COD (mg/L)	205–600	—	390–2072	380–1171	89–643	644–848
Total coliforms (MPN[a] or CFU[b]/100 ml)	4.0×10^5–7.6×10^6 [b]	4.4×10^2–3.7×10^8 [b]	—	0–2.3×10^1 [a]	—	3.8×10^6 [b]
E. coli (CFU[b]/100 ml)	7.0×10^2–5.06×10^4 [b]	5.0–8.6×10^3 [b]	—	1.1×10^4 [b]	—	1.8–2.4×10^4 [b]
References	Zavala et al. (2016); Chrispim and Nolasco (2017); Palmarin and Young (2019); Goncalves et al. (2021)	Leonard et al. (2016)	Noutsopoulos et al. (2018); Sievers and Londong (2018); Jabri et al. (2019); Truu et al. (2019)	Abdel-Shafy et al. (2019); Oktor and Celik (2019); Alrousan and Dunlop (2020); Ucevli and Kaya (2021)	Deng et al. (2020); Perdana et al. (2020); Subramanian et al. (2020)	Oteng-Peprah et al. (2018); Dwumfour-Asare et al. (2020); Raphael et al. (2020)

Abbreviations: BOD, biological oxygen demand; COD, chemical oxygen demand; TN, total nitrogen, TP, total phosphorus; TSS, total suspended solids.
[a]Indicates value for MPN.
[b]Refers to CFU.

rainwater varies according to the type of roof coating materials. Other factors affecting rainwater quality include local emissions, climate conditions, fecal dropping from animals, or even heavy metals and impurities leached from the catchment area due to the slightly acidic nature of rainwater. Even though annual rainfall in tropical climate regions averaged at 59 inches, unpredictable rainfall in certain parts of the world with dry, mild, continental, and polar climate might limit dependence on rainwater as a standalone water source (National Geographic, 2017). Contrariwise, the amount and quality of greywater produced by each household varies and significant differences can be observed between urban and rural regions in a country and across the countries globally (Bodnar et al., 2014). The amount of greywater produced vary from as low as 14 L/day in regions such as Africa and Middle East to as high as 225 L/day per person in other parts of the world (Al-Hamaiedeh & Bino, 2010; Halalsheh et al., 2008; Morel & Diener, 2006). The generation of greywater is also dependent on various factors including number of household occupants, water supply availability, lifestyle, geographical location, water, sanitation and hygiene infrastructures, and climate (Oteng-Peprah et al., 2018). Jamrah et al. (2006) reported 69% of domestic water consumption attributable to greywater production.

The greywater makes up about 75% of the wastewater volume in households (Edwin et al., 2014; Leal et al., 2010) and the high percentage has led many countries to adopt greywater recycling as a supplementary source to freshwater supply. Quality of greywater also varies according to sources of origin such as shower, laundry and washbasins, in addition to factors addressed for variation in the quantity of greywater generated (Oteng-Peprah et al., 2018). Physical, chemical and biological properties of greywater from different regions are summarized in Table 2. The Asian and African households have high turbidity and TSS in their greywater. Greywater generating from kitchen and laundry generally have high turbidity and suspended solids due to actions of washing vegetables or clothes that contribute to food particles, oils, sand, clay, and fabric fibers (Boano et al., 2020; Shaikh & Ahammed, 2020). In addition, the American and Asian households were reported to have high TN compared with other counterparts however within the range reported in literature (4–74 mg/L) (Oteng-Peprah et al., 2018). While high level of nitrogen in greywater originates from kitchen waste, elevated nitrates, and phosphates level originate from the use of soap, laundry detergents, and dishwasher (Boyjoo et al., 2013). Another interesting finding was that the European households showed highest BOD (208–1363 mg/L) and COD (390–2072 mg/L) ranges in their greywater, followed by the Middle-East. BOD measures the biodegradable organic load in water, while COD measurement includes both organic and inorganic matters susceptible to oxidation. The BOD/COD ratios ranging from 0.31 to 0.71 indicate almost 50% of the organic compounds in the greywater are biodegradable (Halalsheh et al., 2008; Oteng-Peprah et al., 2018). The elevated level of BOD and COD in water conventionally due to the presence of emerging pollutants, the xenobiotic organic compounds such as pharmaceuticals, personal care products, endocrine-disrupting compounds, and so on (Oteng-Peprah et al., 2018; Shaikh & Ahammed, 2020). The total coliforms and *E. coli* counts were almost similar across the regions, except low total coliforms observed for the Middle-East. Bacteria in greywater could be from the kitchen, hand basin, or bathroom sources.

Different greywater characteristics across the different continents implied that there would not be a "one size fits all" solution to reclaim greywater for reuse but dependent on the localized characteristics of the greywater and intended use of the treated water. Other factors that could be decisive on the method to implement rainwater harvesting or greywater treatment and reuse are (i) technology readiness, (ii) cost to implement and maintain the system, and (iii) usability of the reclaimed water, which will be further discussed in subsequent sections.

2.3 | Decentralized systems

Water efficiency entails encouraging the sustainable use of water including implementing measures that allow for significant reductions in water wastage, pollution and environmental impacts in the production of commodities and services including domestic water provision (UNEP, 2014). Water efficiency is a practical way to reduce the consumption of the depleting freshwater sources globally. Water efficiency is applicable to both potable water and non-drinking water. Non-drinking water includes rainwater, domestic wastewater and urban (domestic + industrial) wastewater. Wastewater (also called sanitary sewage) normally consists of fecal coliforms (mainly from domestic areas), hazardous inorganic chemicals (heavy metals, nitrates), organic pollutants (pesticides, fertilizers), and emerging contaminants (pharmaceutics, microplastics). Wastewater can cause health burdens to mankind and disturbs natural aquatic life cycle (Tortajada, 2020). Thus, wastewater treatment is necessary to process the wastewater to meet the environmental discharge standards or other quality standards for purposes such as recycling or reuse (Tortajada, 2020; UN, 2020). Besides being the predominant environmental buffer of wastewater discharge, surface water especially rivers is the main source for providing raw water for drinking water treatment plants and hence acting as direct drinking water source for many communities, especially in remote locations of developing nations (Tortajada, 2020). Globally, 1.56% of the population still relies on surface water as drinking water (Ritchie & Roser, 2021a). The number rocketed to 6.84% focusing on just the Sub-Saharan African population (Ritchie & Roser, 2021b). Large change in feed chemistry due to untreated wastewater will affect the water treatment efficiency in the treatment plant and could lead to plant malfunction affecting the drinking water supply of even a larger population. These stress the need to comply with the wastewater discharge standards and regulations.

However in real scenarios, non-compliance to wastewater discharge standards is observed (OECD/Eurostat, 2018). Globally, around 80% of sewage is discharged without prior treatment or recycling. The high-income countries on average treat 70% of the generated wastewater, followed by upper-middle-income countries (38%), lower-middle-income countries (28%), and low-income countries, where only 8% of the wastewater generated is treated (Sato et al., 2013; UNESCO WWAP, 2017). Based on SDG 6 Summary Progress Update 2021, out of 128 countries' data, 56% of the household wastewater is safely treated (UN-Water, 2021). However, no or very little data is available on the proportion of the industrial and agricultural wastewater flow that is safely treated. Untreated wastewater could possibly be explained by the lack of connection between wastewater sources and the centralized wastewater treatment plant. For example, in Poland, 35% of the rural population is not connected to sewage systems (Boguniewicz-Zabłocka & Cappodaglio, 2017). This is more commonly observed in developing countries. Possible reasons for the lack of centralized wastewater treatment facilities in the rural areas of developing countries are, (i) situated further from major treatment centers, (ii) huge investment required for centralized systems in remote locations, and (iii) lack of financial resources and funding support (Boguniewicz-Zabłocka & Cappodaglio, 2017; Peter-Varbanets et al., 2009). The centralized wastewater treatment systems consist of collection, treatment, disposal, collection, and discharge or distribution (if treated water is reused). The sewage collection systems also need an extensive piping infrastructure (Estévez et al., 2022). In addition, the complex and scattered topography of rural areas would increase the capital and maintenance cost of the pipeline (Estévez et al., 2022; Huang et al., 2021). In 2018, only a quarter of China's rural municipal wastewater was adequately treated, where insufficient fund was one of the contributing factors of the treatment plant infeasibility (Huang et al., 2021).

Globally, some countries experience a funding gap of 61% to achieve the SDG water and sanitation targets and only less than 15% of nations have the financial capacity to execute their water development plans (UN, 2019; UN, 2020).

In the next 30 years, the wastewater effluents are expected to rise up to 10%–15% further contributing to water quality degradation (Ahuja, 2019). Wastewater is not only a source of contamination of surface and groundwater resources, but the presence of emerging contaminants will also add complexity to the wastewater recycling process. This will increase the by-now high cost of treatment and management of reclaimed wastewater through centralized systems, making large centralized wastewater treatment systems not the most viable option in urban, peri-urban, or in rural water management. One of the SDG 6 global targets explicitly stated that, by 2030, the need to "expand international cooperation and capacity-building support to developing countries in water and sanitation-related activities and programs, including water harvesting, desalination, water efficiency, wastewater treatment, recycling, and reuse technologies" (UN-Water, 2021). In line with this, localities who lack a centralized wastewater treatment infrastructure could benefit from implementing lower cost and safe water reuse options such as decentralized systems. Decentralized systems could be of a single household or a community scale system. UNESCO WWAP (2017) reported the investment, operation, and maintenance costs of decentralized systems are lower than large-scale systems, in the range of 20%–50% or even more. Thus, rainwater and greywater recycling schemes are feasible small-scale technologies for water reuse. However, there are multiple factors that might affect the sustainability and viability of developing decentralized systems especially in developing countries. The implementation of decentralized water reuse systems is particularly challenging in countries with low water tariff (Chirisa et al., 2017; Lani et al., 2018). In these cases, various strategies such as incentives, microcredit schemes, and subsidies by relevant authorities or the government can be introduced to encourage the adoption of decentralized technologies, preceded with social, economic, and ecological awareness of these water efficient systems. At the government scale, changes in policy and regulation on the implementation of the decentralized schemes as part of integrated water resources management, especially in urban settings that are facing high water stress, are necessary to highlight their importance and for quality control.

2.3.1 | Water quality requirements for various applications

Recycling and reclamation of rainwater and greywater produce water with different qualities depending on the level of water treatment applied. There are different standards adopted by different nations for various purposes such as garden irrigation, agricultural irrigation, toilet flushing, cooling process, or even laundry. Table 3 shows a summary of some standards for main quality parameters in municipal and agricultural water reuse. As it can be seen in the table, reclaimed water for domestic uses has stricter water quality requirements than for agricultural ones, especially in terms of bacterial enumeration. In addition, standards in developed countries such as the United States and the European nations seem to be stricter for both municipal and irrigation water reuse than other countries such as China and Namibia. The water quality standards might be a reflection of a supportive policy environment. The US has written, "Guidelines for Water Reuse" produced in 2012 with each state having its own regulations for reclaimed water (EPA, 2012; Niekerk & Schneider, 2013). However, this may not be the case for other developing countries. In Namibia, currently there is no established law on water reuse, but "The Water Supply and Sanitation Policy" is in place to educate its citizen on water recycling and reclamation (Niekerk & Schneider, 2013).

It is essential for countries to establish guidelines or standards for water reclamation as it allows proper studies to be carried out on different scales of technology and to optimize the process to produce treated water that is safe for consumption, particularly if decentralized treatment systems were to be set up to alleviate water stress. The users will most likely not have expert's knowledge in water treatment and reclamation. When clear standards have been developed, proper measurements can be taken and control measures can be implemented in decentralized treatment systems for compliance and protect users from water-borne diseases.

3 | LABORATORY SCALE AND PRE-COMMERCIALIZED WATER TREATMENT SOLUTIONS

While there are existing solutions in the market, it is imperative that laboratory scale and pre-commercialized water treatment solutions are reviewed and explored as they could potentially address the world's growing demand for clean and affordable water. The solutions reviewed will be categorized according to their capabilities in primary, secondary, and tertiary treatment of water.

TABLE 3 Reclaimed water quality standards for municipal and agricultural water reuse

Reclaimed water quality parameters	Municipal water reuse			Agricultural water reuse			
	United States Environmental Protection Agency 2012	China reclaimed water reuse regulations GB/T 18920-2002	Namibian Water Act 1956[a]	United States Environmental Protection Agency 2012	European Commission-Joint Research Centre 2017	China reclaimed water reuse regulations GB 20922-2007	Namibian Water Act 1956[b]
pH	6.0–9.0	6.0–9.0	6.0–9.5	6.0–9.0	—	5.5–8.5	4–11
Turbidity (NTU)	≤2	≤5	1–5	≤2	≤5	—	10
TSS[a]/TDS[b] (mg/L)	—	≤1500[b]	—	—	≤10[a]	60–100[a]	—
Residual chlorine (mg/L Cl_2)	1.0	1.0	0.1–5	1.0	—	1.0–1.5	0.1–5
Ammonia (mg/L N)	—	≤ 10	1–2	—	—	—	4
BOD (mg/L)	≤ 10	≤ 10	—	≤ 10	≤ 10	40–100	—
COD (mg/L)	—	—	—	—	—	100–200	—
Total[c]/Fecal[d]/ *Escherichia*[e] coliforms (CFU/100 ml)	0[d]	≤3[c]	0–10[c] 0–5[d] 0[e]	0[d]	≤10 or below detection limit[e]	20,000 a/L[d]	100[c] 50[d] 10[e]
References	EPA (2012)	Rodrigues (2021)	Niekerk and Schneider (2013)	EPA (2012)	Alcalde-Sanz and Gawlik (2017)	Rodrigues (2021)	Niekerk and Schneider (2013)

Abbreviations: BOD, biological oxygen demand; COD, chemical oxygen demand; TSS, total suspended solids.

[a]Group A—Water with an excellent quality, Group B—Water with acceptable quality.

[b]Group C—Water with low health risk, Group D—Water with a high health risk.

[c]Total coliforms.

[d]Fecal coliforms.

[e]Escherichia coliforms.

3.1 | Primary treatment methods

Coagulation-flocculation is conventionally effective in removing suspended solids and organic matters from water and wastewater. Examples of coagulants and flocculants are ferric chloride and alum. Ferric chloride at a dosage of 60 mg/L could remove 59% of COD and 73% of TSS from greywater (Antonopoulou et al., 2013). Although ferric chloride works in a wide range of pH, it is very corrosive in nature. On the other hand, alum ($Al_2[SO_4]_3 \cdot 18H_2O$) removed up to 83% of TSS and 99% of *E. coli* in greywater at pH 7.5 (Ghaitidak & Yadav, 2015). Coagulants and flocculants are rarely used as a single-treatment option and commonly paired with other treatment methods such as sedimentation, sand filtration or disinfection. Furthermore, the flocs from coagulation are secondary wastes that could pose environmental issues if not dealt with properly. Therefore, there is a constant search for improved coagulants, especially on the use of coagulants derived from natural sources (i.e., chitosan, *Moringa oleifera*, diatomite) and laboratory scale studies were conducted to identify the optimal coagulant dose for various applications. Diatomite (1.0–2.5 mg/L) added to 50 NTU turbid water during sedimentation stage produced 0.87 log reduction of *E. coli* at pH 5 (Sha'arani et al., 2019). While the laboratory scale studies have shown promising results, the fact that need for conducting detailed study to identify an optimal coagulant dosage has limited the deployment of new types of coagulants for the market due to the need for involvement of an expert in the field rather than a technology managed by non-experts.

Electrocoagulation was also studied to remove organic and inorganic compounds in greywater in the laboratory scale. The electrocoagulation systems consist of a cathode which hydrolyzes water into hydrogen gas and hydroxyl groups, as well as an anode which introduces metal ions as shown in Figure 2. It is advantageous to work with electrocoagulation for contaminants removal in water without need for the addition of chemicals as metallic ions as coagulants are continuously generated from the electrode when current is applied. Only the sacrificial anode, frequently made of aluminum, iron and magnesium has to be replaced periodically. In recent years, electrocoagulation process has been integrated with different treatment processes such as membrane filtration (Khosravanipour Mostafazadeh et al., 2019), ozonation (Barzegar et al., 2019), and electrodisinfection (Cotillas et al., 2020) to achieve higher water treatment effectiveness and efficiency. The implementation of electrocoagulation meanwhile has been impeded since it needs a number of issues to be solved at a larger scale namely: (i) treatment of sludge produced from the process; (ii) power requirements that would make it difficult to deploy in areas with energy security issues, for example: in rural communities without consistent electricity supply; and (iii) lack of sufficient manpower and experts to maintain the system.

Membrane filtration is also often explored in the laboratory scale for water purification given the ease of use. Manouchehri and Kargari (2017) studied the microfiltration of laundry effluent and found that COD (2538 mg O_2/L) and BOD (1190 mg O_2/L) was reduced more than 73.4%, however, the values were higher than water reuse standards. Ultrafiltration could reduce the turbidity and total suspended solids of treated wastewater from a conventional sewage treatment plant up to less than 0.2 NTU, besides lowering COD in the range of 20–60 mg/L (Falsanisi et al., 2010). Hourlier

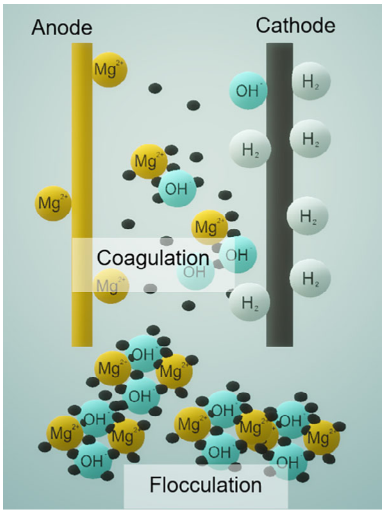

FIGURE 2 The coagulation and flocculation processes in electrocoagulation, where in the cathode, water hydrolyzed into hydrogen gas (H_2) and hydroxyl groups (OH^-), while in the anode, metal ions (Mg^{2+}) are produced

et al. (2010) reported commercial, PCI nanofiltration membranes reduced COD and anionic surfactant in greywater up to 95%, however a very high pressure is required to achieve reasonable water flux. While various membrane materials showed good performance in the treatment of greywater, they have not been widely used for commercial purposes, the difficulties for producing the membranes in huge quantities. Furthermore, the energy requirement to operate a membrane filtration module is high, making it less accessible in areas without stable electricity supply, or for lower income communities. Therefore, the suitability of using membrane filtration for decentralized water reuse remains a challenging question that depends on several factors as outlined above plus capital investment and operational costs.

3.2 | Secondary treatment methods

Biological treatment is often employed as a secondary treatment process to remove biodegradable organic and suspended solids in any types of wastewaters. Centralized treatment systems utilize activated sludge to remove contaminants in wastewater aerobically. Unlike the centralized wastewater treatment systems, the decentralized systems use other biological treatments including biofilter, rotating biological contactor, and membrane bioreactor that have smaller footprint. Biological treatment systems are well studied and are used commercially. However, research works are still being conducted to improve the efficiency of the system, or to reduce the time required to treat the wastewater.

Two types of biofilters are available for greywater treatment, namely macrobiofilters and membrane biofilters. The microorganisms are either attached or suspended in macroporous filters, while membrane biofilters can be submerged into wastewater or installed at the side stream. Santos and Daniel (2020) reviewed the activated carbon filters developed for water and wastewater treatment. The biofilm formation and activity are influenced by the feed water quality, backwashing, hydraulic conditions, and temperature. The activated carbon biofilters could remove 17%–63% of organic matter from wastewater (Hoang et al., 2004; Hoang et al., 2008; Kalkan et al., 2011; Pramanik et al., 2014; Reungoat et al., 2011; Reungoat et al., 2012; Rhim, 2006). Sharaf and Liu (2021) treated greywater using activated carbon biofilter recently and found that total COD removal near to 70% was achievable after 24 h. Germec et al. (2020) also reported an in-sight summary on the biofilm reactors with value-added products such as bioenergy, carbohydrates, antibiotics, acids, vitamins, and enzymes.

Anaerobic biofilter was also integrated with an up-flow anaerobic sludge blanket to treat the black water for simultaneous biogas production (Dorji et al., 2021). Anaerobic biofilter removed up to 98% of COD with a hydraulic retention time of 8 h. The moving bed biofilm reactors could reduce 59% of BOD, 70% of COD, 87.07% of TSS, and 66% of turbidity of greywater if paired with a settling tank (Chrispim & Nolasco, 2017). At the full scale, the multistage moving bed biofilm reactors integrated with sand filter and ultraviolet (UV) disinfection reduced 94.5% of COD, 99.4% of BOD, 91% of DOC, and 99.7% of NH_4-N from the greywater (Saidi et al., 2017). Al-Wasify et al. (2018) treated greywater using a pottery scraps column, followed by a moving bed biofilm and H_2O_2 disinfection. The overall COD removal of 95%, TSS removal of 97.8%, BOD_5 removal of 95.1%, and turbidity removal of 93.6% were attained. Besides that, Eslami et al. (2017) utilized a fixed bed biofilm with activated sludge system to remove 92.52% of COD from greywater. This system also removed linear alkylbenzene sulfonate (LAS), oil and grease as much as 94.24% and 90.07%, respectively. Tombola et al. (2019) reported that the sequencing batch biofilm reactor alone could remove COD as much as 86.5%, ammonium up to 98.4%, and TN near to 71%. COD removal up to 95% could also be achieved after 120 days using multi-chambered anaerobic biofilm reactors with *Proteobacteria* sp. and *Metahnogenic* sp. in the treatment of greywater (Khuntia et al., 2019). Zheng et al. (2020) commented that Proteobacteria, Bacteroidetes, Pseudomonas, and Enterobacter in small diameter gravity sewers could attain COD removal up to 22.31%, TN removal at 21.95%, and TP removal at 6.16%.

Pronk et al. (2019) used microfiltration and ultrafiltration membranes with biofilm for water and wastewater treatment. Jabornig and Podmirseg (2015) treated greywater using PVDF membrane (0.2 μm) with biofilm. The turbidity removal was 97%, COD removal was 69%, and TSS removal is 99%. Zhou et al. (2020) recently applied a membrane biofilm reactor to greywater as well. The COD removal was improved to 88.4%, with LAS removal of 95.6% and TN removal of 80% were recorded. Microfiltration or ultrafiltration membranes are installed in a membrane bioreactor with a small footprint to retain the solid materials produced from biological treatment. Cecconet et al. (2019) summarized the research works related to greywater treatment using membrane bioreactor. Membranes with pore size smaller than 0.45 μm were commonly used, while hydraulic retention time in the range of 0.3–40.8 h was mostly reported. BOD less than 10 mg/L as stated by World Health Organization (WHO) standards could be achieved.

Although great results can be achieved with biological treatment systems in the treatment of greywater, the system is very sensitive to changes and requires to be constantly operated and monitored by experts which could be challenging for many local users. Hence for biological treatment systems to be successfully implemented at a decentralized level, the expertise gap needs to be addressed. In addition to the future development to streamline the expertise requirements, the introduction of artificial intelligence as means to control and monitor progress remotely can be a good alternative for resolving this challenge.

3.3 | Tertiary treatment methods

Disinfection is essential given the treated wastewater will be reclaimed for reuse. The level of microorganisms in the effluent should be within an acceptable concentration to prevent health issues during reuse. Chlorine is a common disinfectant in drinking water, available in the form of compressed gas, sodium hypochlorite solution, or calcium hypochlorite, reacting with water to form hypochlorous acid and hydrochloric acid. The acid produced then kills microorganisms through the destruction of the cell wall and chemical bonds in the cell. However, the use of chlorine will produce harmful by-products such as THM which is cancerogenic for human health. As such, 66 countries have specified a guideline value for residual chlorine lower than the WHO guideline value of 5.0 mg/L (World Health Organization, 2018). Thus, there is a constant search in the laboratory to identify alternative disinfectants that are less harmful to human health and any other living organisms for possibility of reuse.

Performic acid with a concentration range of 0.5–1 mg/L was studied and was found to be able to deactivate S2-coliphages, DNA-coliphages, enterococci and *E. coli*, *Salmonella* spp., *Clostridium perfringens* spores, and Giardia cysts in 10 min (Karpova et al., 2013). Peracetic acid (PAA) forms less halogenated disinfection by products compared with chlorine. Peracetic acid with a concentration in the range of 2–15 mg/L deactivated bacterial (*E. coli*, *Enterococcus* spp.) effectively within 30 min, but less effective than sodium hypochlorite in the disinfection of secondary wastewater at low temperature (4°C) (Hassaballah et al., 2020). Given that acids are corrosive materials, it is not safe for implementation in a decentralized treatment system if the system is to be handled by individuals who are not familiar with the risks associated to the use of acids and proper methods to handle them.

Alternatively, solar disinfection can achieve a reduction in 2.47-log of total coliforms and 3-log of fecal coliforms to meet WHO standard in a study conducted using a tubular photoreactor (Igoud et al., 2015). UV dose of 10 mJ/cm^2 is sufficient to reduce *E. coli* to 5000 CFU/100 ml for discharge to surface water, but UV dose of 30 mJ/cm^2 is required to attain *E. coli* reduction to 10 CFU/100 ml for unrestricted reuse purposes (Antonelli et al., 2008). However, UV disinfection can be affected by turbidity, suspended solids concentration, color, organic molecules, and UV absorbing components such as Fe^{2+} ions. Besides solar and UV-C (wavelength <280 nm) disinfection, UV-LED with long life span and low energy consumption has been studied in water disinfection (Chen et al., 2017). Moreover, photochemical and photocatalytic disinfection have been extensively studied in recent years. UV irradiation induces the formation of hydroxyl, chlorine, and sulfate radicals during photochemical disinfection in the presence of hydrogen peroxide (H_2O_2), chlorine, persulfate, and other chemicals (Moreno-Andrés et al., 2020; Zhang et al., 2019). Formisano et al. (2016) reported that sunlight/H_2O_2 and sunlight/PAA disinfection are effective to reduce *E. coli* in the wastewater to 3.52-log of *E. coli* and 3.13-log of *E. coli*, respectively in 120 min. On the other hand, UV irradiation also induces the formation of hydroxyl and oxygen radicals from water in the presence of photocatalysts such as TiO_2, ZnO, and more. Pablos et al. (2012) compared the effectiveness of TiO_2 free particles and TiO_2 fixed bed reactors in the deactivation of *E. coli*. TiO_2 free particles reduced *E. coli* under the detection limit in less than 160 min, while TiO_2 fixed bed reactor requires more than 320 min to reduce *E. coli* under the detection limit. However, what limits the implementation of such systems are the space required, cost and accessibility to advanced materials for implementation in decentralized treatment system.

Ozone is a strong oxidant and virucide that can be produced by transferring the dry air or oxygen through a high voltage electric discharge. It oxidizes or destroys the cell wall, damages the nucleic acid constituents, and depolymerizes through the breakage of C–N bonds. However, ozone is corrosive and corrosive-resistant materials should be used in the ozone treatment systems. Liberti et al. (2000) reported that ozone is not effective to disinfect wastewater down to 2 CFU/100 ml of total coliforms as attained by UV and PAA treatment to fulfill California standard although it meets WHO standard with 1000 CFU/100 ml of fecal coliforms. USEPA (2010) suggested that ozone Ct (concentration × time) of 1.8 (mg/L)-min is required to achieve 4-log reduction of viruses at low temperature (<1°C). Sigmon et al. (2015) later confirmed that the inactivation of *E. coli*, Coxsackievirus B5, Poliovirus 2, Adenovirus 2, φX174, and PRD-1 more than

4-log should be conducted using ozone Ct between 0.1 and 1.0 (mg/L)-min. Similar to the use of acids, ozone also has to be handled by experts given that it has strong oxidizing strength, making it less suitable for implementation in a decentralized treatment system where it is expected to be manned by non-experts.

Ultrafiltration disinfects the treated wastewater from a conventional sewage treatment system, achieving *E. coli* count to be lower than 10 CFU/100 ml for unrestricted water reuse purposes according to Italy and US standards (Falsanisi et al., 2010). Mazuki et al. (2020) conducted a techno-economic evaluation on UV, chlorination, microfiltration, and ultrafiltration for water reuse. Chlorination and UV integrated with Enviromultimedia (a biofilm media) were rated to be the most cost-effective for restricted reuse purposes, while ultrafiltration is most economical for unrestricted reuse purposes.

Conventional technologies for water and wastewater treatment do not involve virion removal. The reuse of treated water or wastewater resulted in an increasing concern on the high influential viral loads during a pandemic. In a study by Wölfel et al. (2020), about 67% of feces samples which tested positive showed SARS-CoV-2 RNA counts near to the maximum counts sputum. More studies detected SARS-CoV-2 RNA in wastewater samples (La Rosa et al., 2020; Randazzo et al., 2020). The dose of chemical disinfectant required further adjustment during the pandemic. Since the efficiency of tertiary treatment such as ozone, UV radiation, advanced oxidation remains unknown, ultrafiltration is recommended as the porous membrane with pore size within 2–50 nm is sufficient to remove SARS-CoV-2 with a diameter of ~100 nm (Bogler et al., 2020). This further justifies the importance of having proper reclaimed water quality standards for decentralized treatment systems to prevent sources of reclaimed water from becoming a threat for human consumption.

Out of all the different technologies outlined above, membrane technology seems to have the greatest potential to be developed as a solution for decentralized water/wastewater treatment. This is due to the versatility in customizing the materials used to fabricate the membrane to suit the purpose of reclaimed water—additional materials can be introduced to enhance certain functions (i.e., disinfection) of the treatment process. However, further investigations need to be done before any of these materials and technologies can be scaled up for practices of rainwater harvesting or greywater treatment and reuse.

4 | IMPLEMENTED SOLUTIONS IN THE MARKET

4.1 | Rainwater harvesting

Rainwater harvesting collects rainwater for reuse purposes onsite within the rainfall and hence stops contributing to surface runoff and minimizes the risk of flooding in sewer systems. Rainwater harvesting systems range from using simple pails at the back of home, rain barrels (butts) to more elaborate designs with tanks, purification systems, and pumps. Rainwater harvesting is one of the most cost-effective approaches to tackle the water scarcity obstacle. Different rainwater harvesting technologies are available in the market with the registered market value of around USD 9000 million in 2020 (Expert Market Research, 2020). According to the Global Rainwater Harvesting Market Outlook Report, the market value is projected to increase with a compound annual growth rate of 4.5% from 2021 to 2026 through analysis of global markets comprising North America, Europe, Asia Pacific, and the rest of the world (Expert Market Research, 2020). Adoption of different rainwater harvesting technologies across the global market for water reuse is based on four basic components including catchment area, storage tank, treatment, and recycling application.

4.1.1 | Catchment area

Rainwater can be commonly harvested from rooftops and impervious surfaces. For the rooftop, the rainwater follows the slanted roof to be collected at the end of the roof by a gutter that channels the water through a vent pipe into storage tank (Pala et al., 2021). On the other hand, impervious land runoffs include collecting rainwater from pavement, road and footpath areas. The catchment area affects the quality of harvested rainwater. Water collected from roof areas will be of better quality than others due to minimal contact with contaminants on land and thus, require less complex purification processes (Samuel et al., 2012). Therefore, roof harvesting systems are commonly explored for housing and industrial areas for non-potable uses, whereas surface runoff based harvesting systems such as pond systems are widely utilized in farming land for irrigation purposes, where the water quality requirement is less stringent (Zabidi et al., 2020). For the roof harvesting system, the material used for roof and effective roof area will affect the quality of water and efficiency of water collection respectively (Li et al., 2010). For example, Mostafa and Shafiuzzaman (2008) reported rainwater collected from concrete roofs had higher suspended and dissolved solids, while galvanized roofs had higher heavy metal content such as iron and zinc. Certain systems in the market specify the type of roof material needed to be compatible with their systems especially for treatment facilities (Innovative Water Solutions [IWS], 2020).

However, in many low income regions including the remote locations and informal settlements, proper roofing for rainwater harvesting may be unavailable. The roof types in these regions range from mud roof, grass hut, thatched roof, pitched zinc roof with no interconnection and recycled-material composed roof. In these areas, different strategies have been adopted previously. In South Africa, mud dams, dug ponds, stone terracing, and bed gardening are still used in many rural areas for water supply (Kahinda & Taigbenu, 2011). Nowadays, the simple concept of using a whole tank with gutter system as collection surface and storage container with no need for additional expenditure on piping equipment for channeling the rainwater from different catchment area makes the system easy for adoption in areas with no built-in water distribution piping systems (Heritage Tanks, 2016). Besides, for a single household with limited space available and low water requirement, a low cost inverted umbrella can be a feasible option (Hammed et al., 2017; Pala et al., 2021). In a study in Nigeria, rainwater collected from the umbrella harvester had lesser TSS (0.82 mg/L), TDS (32.97 mg/L), total hardness (10.67 mg/L), and nitrate (1.58 mg/L) than rainwater from galvanized roofs (TSS: 4.02 mg/L; TDS: 41.67 mg/L; total hardness: 36.33 mg/L; nitrate: 5.38 mg/L) (Hammed et al., 2017).

There is also an uptrend in man-made nature based catchments built specifically for rainwater harvesting. In Singapore, a similar umbrella concept but with advanced technology was introduced, that is Supertrees towers. The towers are composed of solar photovoltaic systems to capture solar energy, act as rainwater harvesters and function as a garden supporting growth of around 162,900 plants (Solaripedia, 2014). Other catchments include green roof and green wall. In comparison to the general roof which acts as merely an impermeable capture area, a green roof with vegetation and substrate on it functions as catchment, storage, and filtration system concurrently. Green roofs reduce the rate and volume of stormwater runoff. Green wall works on similar principles and is commonly adopted in commercial areas, improving the visual amenity of the building. Retrofitting of green walls is easier on commercial buildings due to accessibility of elaborate pipe networks for installation. In short, the choice of rainwater catchment area and its type are dependent on the fitting area and the installation place as a single-house (detached or semi-detached) residential area, apartments/block of flats (housing estate) or commercial building. For any of these catchment states, an appropriate decentralized rainwater harvesting scheme can be found in the market but usually needs to be customized to obtain a cost-effective design and optimal performance of rainwater collection.

4.1.2 | Storage tank

Storage tanks are constructed using different materials and come in various designs in the market. Metal, polyethylene, cement-brick, and ferro-cement are generally used materials (Islam et al., 2010; Li et al., 2010). The size of the storage tank is chosen based on the size of the catchment area, level of rainfall, and daily water requirement (Li et al., 2010). In general, storage tanks can be installed above ground and underground. Few advantages of above ground systems are lesser energy required to distribute water for reuse via gravity flow, easy detection of leakages, and cleaning work (Zabidi et al., 2020). However, the tank will occupy precious space around the house and not aesthetically pleasant. For aesthetically appealing residential rainwater harvesting systems, there are a wide variety of choices for designer rainwater vessels (modern, rustic, free-standing rainwater tank, wall-mounted tank with or without integrated planter pot) in the market (Bacfree, 2021). On the other hand, the underground rainwater harvesting system can save space around the house. However, it involves higher cost due to underground digging and construction and more energy for distribution. To overcome this disadvantage, there are tanks available with shallow dig design which mean less ground required to excavate, less cost, easy maintenance, and up to 80% less digging work (Graf, 2021; Stormsaver, 2021). While underground installation while might protect the tank from sunlight induced evaporation, this will limit easy inspection for leakage especially in underground with a web of tree roots that can damage the tank, has higher risk of contamination and need for higher power pump to extract water for distribution (Zabidi et al., 2020). Storage tanks for different scales of decentralized rainwater harvesting schemes are common in the market but new forms that are more efficient and effective for installation and water quality protection fit for specific applications need to be improved with further investigations in the future.

4.1.3 | Treatment and recycling

Filtration system

The rainwater from the rooftop might be contaminated with dust, dry leaves, bird droppings, microbes, or even heavy metals corrodes from the roof material and has to be purified to varying degrees depending on its water reuse application. The filters used in the market range from a simple screener to sophisticated filters which will dictate the purpose of water reuse. Primary filters such as the first flush diverter or collector present in most rainwater harvesting systems as shown in Figure 3 (Heritage Tanks, 2016; IWS, 2020; WISY, 2020). It functions to discard the first collection of rainwater as there might be accumulated contaminants from dirt on the roof. There are two types of filters in the market for that function based on a unique concept. The vertical filtration system functions as both first flush and filter with

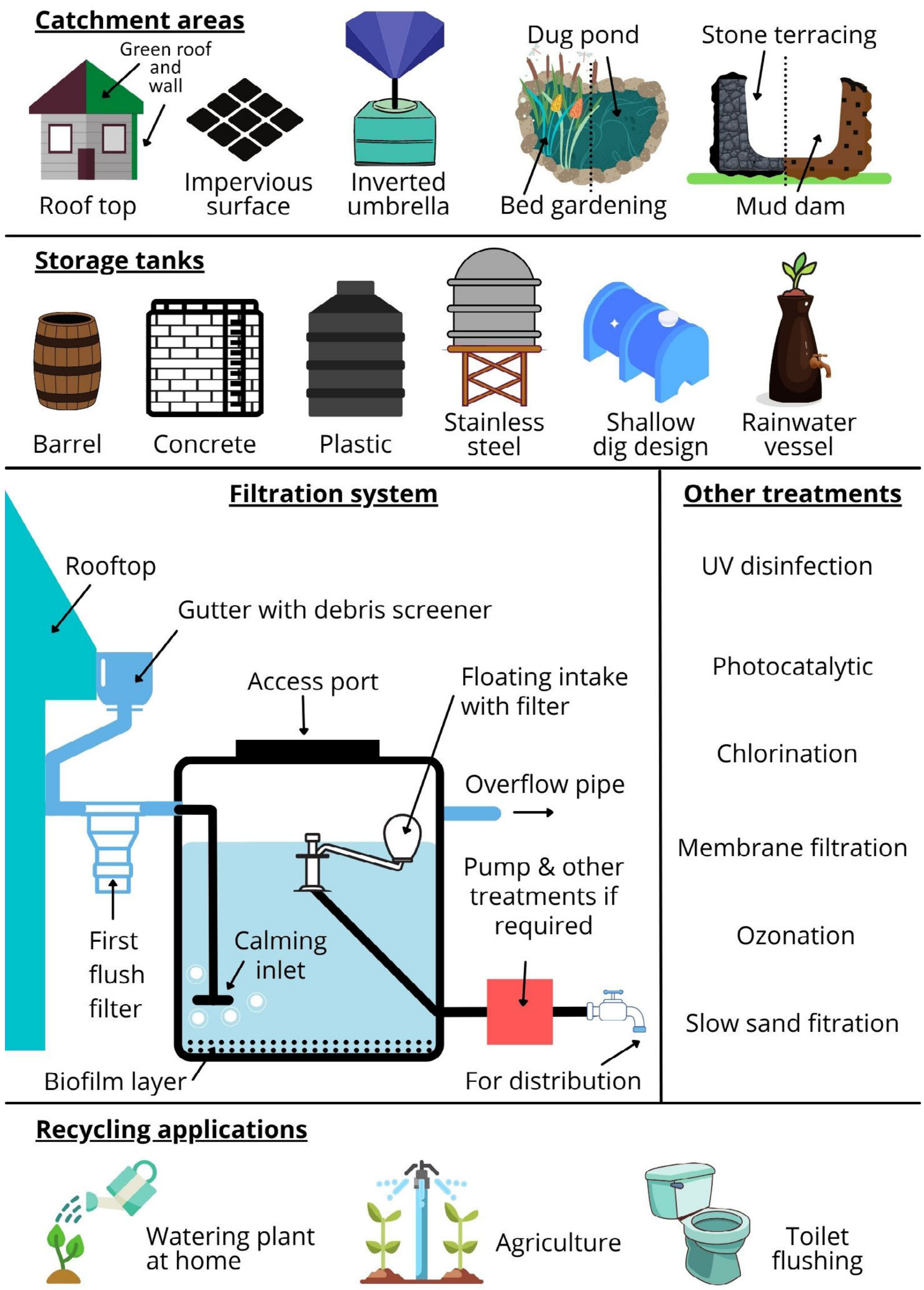

FIGURE 3 A summary of rainwater harvesting with four basic components including catchment areas, storage tanks, treatments, and recycling applications

90% efficiency in collecting rainwater (WISY, 2020). The vertical filter mesh works based on the physics law of water, namely, adhesion, cohesion and gravity. The remaining 10% of the rainwater used to self-clean the device, thus preventing any blockage of the filter. The second filter is the dual intensity self-cleaning rooftop rainwater harvesting filter (D&D Ecotech Services, 2021; Water Field Technology, 2021). This self-cleaning device has efficiency above 90% to channel treated water into storage tanks (Rainwater Harvesting, 2015). The simple design of the filter allows it's mounting to a wall and occupies very little space and can be used for both individual house and apartment-type households. There is no special requirement for the storage tank and thus allow for flexibility of using tanks available locally. In the storage tank, the predominantly adopted primary filtration mechanism is physical method via sedimentation and together with calming inlet to prevent the disturbance to the layer of healthy biofilm layer that formed by small quantities of sediment present in the rainwater despite the prior filtration process, overflow siphon to remove floating particles such as pollen or dust forming a layer on top of the rainwater when the tank overflows and floating suction filtration in some products to ensure the intake of cleanest water from right below the water surface (IWS, 2020; Watts, 2017; WISY, 2020). The water can be distributed for garden irrigation or pumped for storage to be used later for non-potable water reuse such as toilet flushing and washing vehicles. In certain localities, activated carbon and charcoal filters which work on the principle of adsorption are easy and inexpensive to find are used to remove impurities such as heavy metals and reduce odor from rainwater, especially in low income regions (Islam et al., 2010).

Natural filtration

Apart from the filtration systems discussed above, nature-based filtrations are also gaining popularity such as green roofs and walls. Green roofs can be either extensive or intensive for functional purposes only or for aesthetic look too respectively (Laminack, 2014). Extensive green roofs are almost five times shallower than intensive roofs and covered with stress tolerant and smaller plants (require less growth media) (Laminack, 2014). Besides functioning as a rainwater sponge and reducing the burden of stormwater drainage, the green roofs can improve a few quality parameters of rainwater such as reducing its acidity and nitrate-ammonium content (Laminack, 2014). However, green infrastructure harvesting methods in general produce rainwater of lesser quality than those collected by rooftops. Green wall works on similar principle but follows vertical structural design. The collected rainwater can be used directly for irrigation of commercial and residential buildings' landscapes, besides toilet flushing.

Secondary treatments

In order to convert harvested rainwater to potable water, sophisticated treatment is required such as UV disinfection, photocatalytic, chemical treatment (e.g., chlorination), membrane-based filtration, ozonation, and slow sand filtration (Buntat et al., 2015; Lani et al., 2018; Omar et al., 2017). Suitability of the treatment method depends on the water quality requirement for reuse and cost of the treatment system. In general, the cost of operation and maintenance of a rainwater harvesting system is economical if a simple water purification system is chosen for non-potable uses. Successful implementation of the rainwater harvesting system is multifactorial including tax relaxation, local authority incentives, and public awareness. For example, in Uganda subsidies are provided for rural households to buy rainwater harvesting system construction items, while in Germany, stormwater taxes are exempted for premises that practice rainwater harvesting (Lani et al., 2018). While rainwater harvesting is gaining its popularity, greywater recycling potential for water reuse is also tapped worldwide.

4.2 | Greywater recycling

Compared with rainwater harvesting that is dependent on the weather pattern and specifically wet periods, greywater is a more reliable alternative as a continuous water supply source. Greywater recycling systems range from very basic to advanced methods of recycling. Unlike rainwater harvesting that can be used without any treatment, the collected greywater needs to undergo a certain level of treatment before it can be used even for non-potable purposes. Some of the commonly used treatment techniques include physicochemical (filtration, adsorption, and reverse osmosis) and biological (membrane biological reactor, rotating biological contactor, biological aerated filter, and waste stabilization ponds) methods (Sivakumar & Ramezanianpour, 2012). The greywater recycling market is driven by increased need to look for freshwater resources alternatives, government incentives and public awareness. The market is predominantly segmented based on the treatment systems and applications. Direct reuse of collected greywater is seldom used in commercial settings and the concept of laundry-to-landscape is more prevalent in residential areas. Unlike rainwater, collected greywater has to be reused promptly since chemical parameters such as BOD and COD can change significantly within a short time period (Li et al., 2010). The British Standard BS8525-1:2010 outlining the Greywater Systems Code of Practice advised against using greywater for applications requiring higher water quality including bathing and dishwashing (BSI, 2010). The technologies used for greywater treatment can be classified under three systems (one-stage, two-stage, and multi-stage) that are critically analyzed below.

4.2.1 | One-stage system

To date, there are a few companies producing one-stage process system, where the water is reused within a short residence time to prevent significant changes to the chemical parameters of greywater and only minimal treatment necessary (, 2020b; Aqua2use, 2018a; Aquarius Wastewater Management Systems [AWMS], 2020a). Coarse filtration is the common type of one-stage process system—typically using in-line bag filters, mesh filters and filtration media (Hitchner, 2016; Matala Water Technology Co., Ltd, 2011; Pure Water LLC, 2010). The filter pore size ranges from about 100 μm to even as low as 5 μm and dictates the quality of treated water produced. When influent passes through the filtration unit, the suspended solids are trapped building the biofilm. It comes in various surface areas and shapes. Increasing the surface area of the filter will improve its sludge holding capacity. One-stage treatment system is a compact above ground system and can be powered by normal domestic electrical supply (Aqua2use, 2018a; AWMS, 2020b). It is available at small scale such as small homes and the main application of water reuse is almost always for lawn and garden irrigation only. The only maintenance work required is periodic cleaning of the filters. Green technologies are also used in greywater recycling. One example is the constructed wetland as a low cost and low impact system, especially for rural areas or small communities in developing countries (Collivignarelli et al., 2020; Oladoja, 2017). Vertical flow constructed wetland functions as one continuous physical and biological filtration system without the need of a preliminary settling tank (Goncalves et al., 2021; Oladoja, 2017). Native species of wetland plants can be chosen for water purification. While the household greywater reuse is more prevalent among the developed countries, this concept is still at its elementary stage and on-site decentralized systems such as wetlands is recognized as appropriate technology in under-resourced countries (Oladoja, 2017). Constructed wetlands such as reed beds are also adopted in developed countries due to dual functions of the eco-pond which are captivating green landscape and sustainable water recycling systems (Stefanakis, 2020). Other examples of green technologies are using natural filtration systems such as green roofs and walls which serve the dual purpose of urban cooling and water recycling.

4.2.2 | Two-stage system

Filtration and disinfection

Two-stage system consisting of filtration and disinfection is the most common technology used for domestic greywater reuse. There are products in the market that utilize coarse filtration and chemical disinfection, coarse filtration and non-chemical disinfection, membrane filtration and chemical disinfection, and multimedia filtration and chemical disinfection (Aquaco Water Recycling Ltd [AWR], 2021a; 2021b; AWMS, 2020c; Greyter, Inc, 2021a, 2021b; Hitchner, 2016; Pure Water LLC, 2010). Coarse filtration normally involves metal strainer, mesh/ gauze filter, bag filters, organic clay filter, polymeric filtration media, and disc filter. Ultrafiltration membrane technology produces better quality treated greywater due to smaller pores with size ranges from 0.01 to 0.1 μm. However, higher pressure is needed to function hence higher energy consumption is required compared with other conventional filtration technology (Li et al., 2010). Another factor restricting its economic viability is membrane fouling that reduces the efficiency of membrane filtration (Ezugbe & Rathilal, 2020). Thus, greywater treatment systems in the market commonly use hybrid membrane processes where other purification methods are used as pretreatment to reduce membrane fouling. In contrast, multimedia filters consist of different layers of media such as sand, coal, and gravel which are of varying size to purify water. The multimedia greywater system is often targeted at the Middle Eastern market that conventionally uses sand filtration treatment methods for rapid filtration (AWR, 2021a). This system has a very small footprint, fast filter rate, low maintenance, and running cost (AWR, 2021a). Chemical disinfection is achieved by dosing of chlorine, bromine or sodium hypochlorite solution (AWR, 2021a; 2021b; Greyter, Inc, 2021a, 2021b; Pure Water LLC, 2010). Other chemical free disinfection processes in the market are UV disinfection, ozonation, and electrolysis (Aqua2use, 2018b;

AWMS, 2020c; Hitchner, 2016). The applications of greywater treated by filtration and disinfection processes are mostly limited to lawn irrigation and toilet flushing.

Filtration and biological treatment

For applications that require a more stringent water quality such as laundry, filtration alone or filtration, and disinfection may not produce treated water that meets the quality standards. Hence, biological treatment is required in these cases to complement the filtration process to remove the organic matter in the greywater. There are few treatment systems in the market that combine mechanical and biological treatments such as membrane bioreactor (MBR) (Aqua2use, 2018b; Aquacell, 2021: AWR, 2021c). MBR is a combination of an activated sludge reactor and a filtration unit. Activated sludge produced via aeration to create ideal conditions for breakdown of biodegradable material. A line of filtration units available in the market range from polymeric biofilter, ultrafiltration membrane and microfiltration membrane (Aqua2use, 2018b; Aquacell, 2021). Even though this system has higher energy demand compared with basic filtration-disinfection systems, it produces treated water with higher quality that can be used additionally for washing clothes. Routine membrane cleaning is required for the system to operate optimally. MBR are available at different scales and can be configured into available space just like other technologies.

4.2.3 | Multistage system

Technologies in the market could not be easily categorized as one-stage or two-stage systems because a complete system almost always comprises multiple treatment process units, especially those to be used for higher quality water production. Sedimentation tanks are present in almost all greywater treatment systems and precede any other processes. Other physicochemical methods used are activated carbon, coagulation, aeration, and clarification. In general, the cost of the greywater recycling system is dependent on sophistication of the technology, water reuse application, maintenance, and ease of retrofitting/renovation needed (Li et al., 2010). Right technology for a particular chosen application will ensure substantial financial savings. Advanced treatment technology for just basic use such as lawn irrigation in a residential area might not be economically viable.

There are ever growing technological advancements of water-saving technologies in the market. However, there are technologies that failed to scale up despite widespread promotion due to the lack of flexible water management framework, changing dynamics of the competitive water market, pricing, and social constraints to adopt those technologies, especially this is the case in the urban settings. This requires that a comprehensive conceptual framework is developed for urban water reuse that will be further discussed in the next section.

5 | CONCEPTUAL FRAMEWORK OF WATER REUSE STRATEGIES

Understanding of current technological developments of water reuse in the market is necessary for the technology adoption and incorporating into urban water systems. However, having access to these technologies per se cannot guarantee their adoption and applications by the public or water utilities. This is mainly due to the fact that the main dimensions of the sustainability framework (i.e., economic, social, environmental, governance, and asset aspects) need to be satisfied when introducing strategies based on these technologies (Behzadian & Kapelan, 2015a). Hence, development of urban water reuse strategies first requires a conceptual framework to include all relevant metrics or key performance indicators (KPIs) derived from the assessment criteria taken from the sustainability framework. Note that creating an exhaustive list of KPIs for water reuse technologies can be challenging and hence the decision makers should select only a limited number of those KPIs that are of interest to the stakeholders and the public. Some examples of these KPIs for water reuse schemes in urban water systems are capital or operation and maintenance costs, efficiency, total contaminations, reliability/resilience/vulnerability of water supply, flood volume, greenhouse gas emissions, public acceptance, usability, and so on. These KPIs can be quantified by either quantitative methods such as water balance conceptually- or physically-based models or qualitative methods such as surveys or questionnaires filled out by the public, experts, or stakeholders. Various techniques have been used in the literature for assessment of water reuse-based technologies based on a number of defined KPIs such as reliability assessment of industrial wastewater reuse by using combined event tree and fuzzy fault tree analysis (Piadeh et al., 2018). After the assessment of potential water reuse strategies for all KPIs individually, the strategies need to be analyzed and compared through either ranking

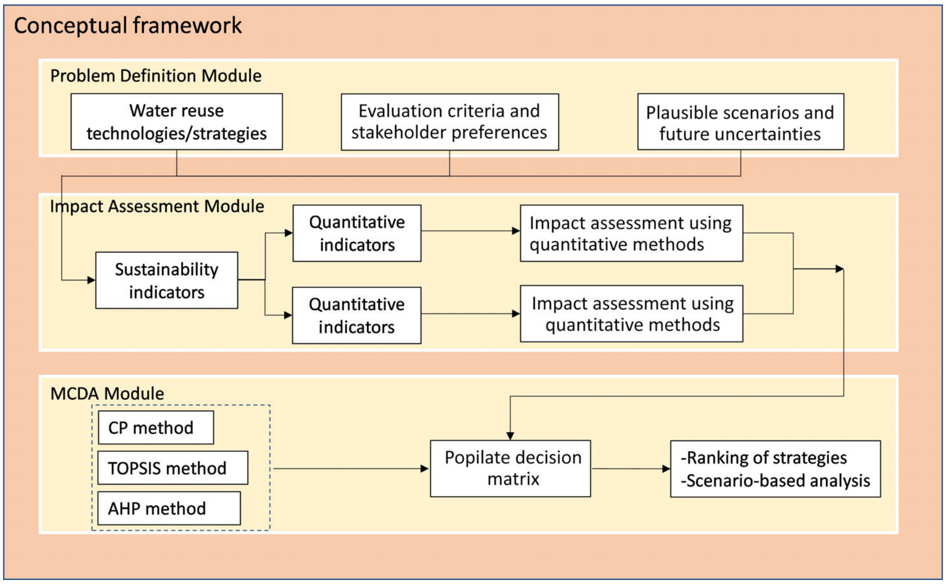

FIGURE 4 Conceptual framework suggested for water reuse decision making

the strategies with respect to all analyzing KPIs (Morley et al., 2016) or a scenario-based analysis to track all plausible consequences of the analyzing strategies (Momeni et al., 2021). This can be performed via a suitable multicriteria decision analysis (MCDA) such as compromise programming (CP) method (Behzadian & Kapelan, 2015a) or fuzzy analytical hierarchy process (AHP) method (Ardeshir et al., 2014).

Figure 4 shows a sample of a conceptual framework for water reuse decision making. This framework can be based on three main modules including (1) problem definition; (2) impact assessment; and (3) MCDA. In the first module, water reuse technologies are selected and hence relevant strategies are formed. Evaluation criteria derived from the sustainability framework are also determined mainly based on the stakeholder preferences. Within the second module, KPIs are identified and the water reuse strategies are evaluated by either quantitatively for quantitative KPIs or qualitatively for qualitative KPIs. The impact assessment will feed the population matrix in the third module in which the strategies are either ranked by using an MCDA method or analyzed based on the plausible scenarios.

5.1 | Why is urban water management important?

In addition, urban areas, the hotspots of water use worldwide, are facing water sustainability obstacles including fragmented urban water management. Water security is defined as "the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability" (UN Water, 2013). The Sustainable Development Goals (SDG) were adopted by all the United Nations Member States in 2015 with 17 SDGs, which calls for global action in reducing inequalities to end poverty and other deprivations (UN, 2020). In particular, SDG number 6 is to ensure availability and sustainable management of water and sanitation for all.

Despite the progress since 2000, 2 billion people (26% of the global population) still have no access to safely managed drinking water services and 29% of the world population have no basic hand washing facilities with soap and water in their dwellings (UN-Water, 2021). While health is a central quality of life indicator, poor health is often contributed by inadequate provisioning of basic needs such as safe, affordable and accessible water, especially in developing countries. Unsafe sanitation contributed to 775,000 deaths annually (Ritchie & Roser, 2021b). In 2020, 46% of the world population had no access to safely managed sanitation and 6% of the world was practicing open defecation (Ritchie & Roser, 2021b). Childhood diarrhea is significantly correlated with poor sanitation, poor hygiene or unsafe drinking water (UNICEF & WHO, 2019). Consumption of untreated and contaminated water due to unsanitary waste disposal has resulted in 1.7 billion diarrheal diseases in children under 5 years old and in 2017, 533,768 children died of diarrheal diseases (Dadonaite et al., 2019; WHO, 2017). Accessibility to safely managed water is a wicked problem. There is no direct strategy to solve this problem as there are few interlinked challenges acting as barriers, including growing water demand and scarcity, water pollution, and the impact of climate change on water availability.

Population expansion, climate change, and urbanization are putting strain on urban water infrastructure systems of cities worldwide, especially in developing countries. According to UNESCO (2018), there are 763 million internal migrants which is more than three times that of 258 million foreign migrants, globally. The disparity in a monthly income of the urban and rural populations has led to the megatrend of internal migration of the rural communities to the metropolitan cities. For example, in Indonesia, the world's fourth most populous nation, almost 50% of the population reside in urban areas, where rural–urban migration is top of the charts (UNESCO, 2018). Urban migration goes along with the vast expansion of informal settlements, congestion, growing food demand, water resources degradation, and inappropriate management of water, sanitation, and waste disposal services (International Water Association, 2018). These challenges emphasize the need for sustainable urban water development now more than any previous time.

The goal of urban water development is to create adaptable, comfortable living, productive, and sustainable townships. One important element to address water-related concerns is the environment–water interface, thus nature-based solutions might provide a more sustainable water use efficiency (UNESCO, 2021). To close the water loop of cities for better water sustainability, diversifying the water sources through maximizing water collection by capturing every drop of rain that falls in the land and rendering water an endlessly renewable resource through wastewater reclamations are among the strategies that could be adopted. The technologies introduced in this study provide opportunities to form intervention strategies based on harvesting rainwater and reusing greywater for future planning of urban water systems. This is important because the assessment of intervention strategies for integrated urban water systems shows those strategies that include water reuse technologies are ranked high and more advantageous than other conventional ones (Behzadian & Kapelan, 2015a, 2015b). Furthermore, as the demand for clean, safe water increases, these technologies that are potentially applicable for decentralized schemes can offset the need for solely relying on centralized water supply. An understanding of the benefits of each technology and the resultant output for use is therefore crucial in designing a flexible system for reuse, capable of adapting to various local and climatic conditions.

Table 4 shows a number of sustainability indicators for two types of water reuse technologies with their options. This synthesis was arrived at by aggregating and mapping rainwater and greywater technologies and its application across the major sources (household-individual and urban-local) to mainly show the potential of these technologies and the ability to expand these to similar infrastructure types. The hotspots for the usability of the technological tools in urban setting can be categorized into residential, commercial and industrial areas, urban farming, and informal settlements which will be briefly discussed in the next section.

5.2 | The hotspots for water reuse in urban setting

The traditional urban water management consists of public water system connecting the centralized water treatment plant to end-users, sewerage system (in certain areas), and finally, wastewater treatment plant (if available) to discharge treated or untreated wastewater as shown in Figure 5. The design of the traditional urban water management follows linear economy, where freshwater resources are taken, treated into potable water quality, used, and released back into the environment as low quality wastewater. In order to accelerate the progress toward achieving sustainable urban water development globally, circular economy should be adopted for a more holistic water resources management. One way to achieve this is by practicing water reuse via rainwater harvesting and greywater recycling in a small or large scale (Figure 5). The circular economy concept can be applied to a whole country or to particular hotspots in urban areas.

5.2.1 | Residential, commercial, and industrial areas

Residential, commercial and industrial areas are inherently part of the urban water management and supplied with the municipal water systems. The public water system is commonly sourced from depleting freshwater sources. Decentralized systems would help to reduce the dependence on the centralized water supply. Residential areas could benefit from both rainwater harvesting and greywater recycling. It will be advantageous to mix the two water sources

TABLE 4 A number of sustainability indicators for rainwater and greywater technologies with their supply expansion potential (information on filtration, technology, and source adopted from Boano et al., 2020)

Type of water reuse and treatment	Specific technology	Scale		Source of water reuse	Usability/place of consumption	Water supply expansion potential
		Household	Urban			
RAINWATER						
Nature-based filtration	Constructed Wetlands/ bioswales	X	X	Street runoff, Roof	Agriculture, recreation, toilets flushing	High
	Green wall	X		Roof	Toilets flushing/ agriculture	Low
	Green roof	X		Roof	Toilets flushing/ agriculture	Medium
Physical filtration	Sedimentation tank + sand filter	X		Street runoff, Roof	Toilets flushing/ agriculture	Medium
	Sedimentation tank + granular active carbon	X		Street runoff, Roof	Toilets flushing/ agriculture	Low
GREYWATER						
Nature-based filtration	Constructed Wetlands/ bioswales	X	X	Shower, sinks, bath, kitchen	Toilets flushing/ agriculture	High
	Green wall	X	X	Shower, sinks, bath, kitchen	Toilets flushing/ agriculture	Low
	Green roof	X	X	Rainwater	Toilets flushing/ agriculture	Medium
Physical filtration	Activated charcoal (charcoal)	X	X	Bath, laundry	Toilets flushing/ agriculture	Medium
	Sedimentation tank + sand filter	X	X	Kitchen	Toilets flushing/ agriculture	Medium
	Hybrid granular active carbon electrochemical system	X	X	Shower/bath	Toilets flushing/ agriculture	Medium
	Sedimentation tank + granular active carbon	X	X	Kitchen	Toilets flushing/ agriculture	Medium
Chemical filtration	Coagulation		X	Shower, sink/ bath	Agriculture	High
	Electrocoagulation		X	Shower, sink, kitchen	Agriculture	High
	EC/O3/UV		X	Shower, sink	Agriculture	High
	Photocatalytic fuel cell		X	Laundry	Agriculture	High
Biofiltration	Rotating biological contactor		X	Laundry, bath, kitchen	Agriculture	High
	Moving bed biofilm reactor		X	Laundry, bath	Agriculture	High
	Membrane bioreactor		X	Laundry, bath, kitchen	Agriculture	High

(Continues)

TABLE 4 (Continued)

Type of water reuse and treatment	Specific technology	Scale Household	Scale Urban	Source of water reuse	Usability/place of consumption	Water supply expansion potential
	Up-flow anaerobic sludge blanket		X	Shower	Agriculture	High
	Biological activated membrane bioreactor		X	Bath, sink	Agriculture	High

Note: The water expansion potential refers to the adaptability and ease of development in communities, leading to the potential of a higher rate of use and the ability to expand or increase the water supply in developing communities.
Abbreviations: EC, electrocoagulation; O3, ozonation; UV, ultraviolet.

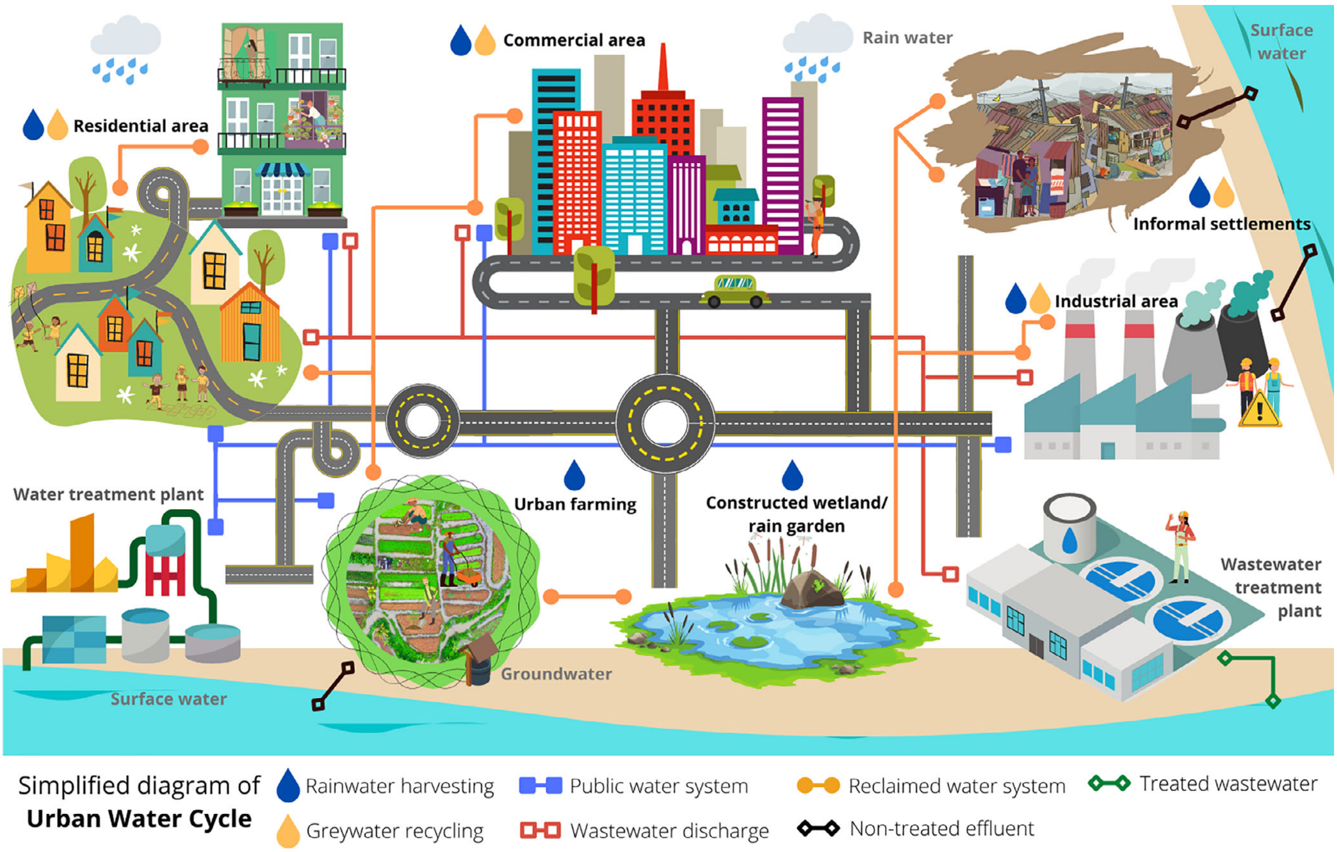

FIGURE 5 A simplified diagram of urban water cycle, where rainwater harvesting and greywater recycling can be adopted in addition to conventional centralized water supply in urban water management

because sometimes the amount of rainwater is insufficient to provide supply for non-potable reuse and greywater is consistently available. The treatment of rainwater together with greywater will lower the concentration of materials that needs to be removed. But the inconsistent supply of rain may imply that the system has to be robust enough to deal with occasional changes in feed characteristics. Reclaimed water in these localities has low to medium water supply expansion potential and thus more commonly utilized for on-site toilet flushing and garden irrigation. Nature-based and physical filtration technological tools are more suitable to produce water for reuse. Capitalizing on water-saving strategies which are focused on nature-based filtration can therefore serve as a ubiquitous and accessible method for many socio-economically disadvantaged communities to expand their water supply. Constructed wetlands and bio-swales are also gaining popularity in the latest townships. Green walls and roofs also can be retrofitted into larger buildings, that is, condominium and commercial buildings. Besides helping to save water, these green technologies add aesthetic value. When coupled with water-saving fixtures and appliances, and efficient irrigation technologies and practices, these filtration technologies can increase clean water accessibility significantly with high community acceptance in these areas.

5.2.2 | Urban farming

The United Nations World Water Development Report (2021) stated one of the water management strategies for food production is obtaining water for irrigated agriculture, mainly from nature-based and non-conventional sources (UNESCO, 2021). In communities where reclaimed greywater is still not accepted for domestic use, the recycled water can be channeled to the nearest urban farms. Urban farming is gaining popularity in countries like India, Ghana, Kenya, and Vietnam, to name a few. For many developing countries, agriculture contributes a smaller share of income compared with industrial sectors, it however, consumes largest volumes of water, contributing to 70% of freshwater withdrawal globally (Ritchie & Roser, 2017). Indonesia is the largest agricultural water consumer in Southeast Asia, at nearly 92.76 billion m^3, followed by Vietnam and Philippines (Ritchie & Roser, 2017). Urban and peri-urban farms produce 80% and 40% of the total of fresh vegetables and eggs, respectively, in Hanoi, Vietnam (Corbould, 2013). In Ghana's capital, almost 90% of consumed vegetables are produced within the city (Corbould, 2013). Improvement in crop productivity with a lower percentage of freshwater use should be the way forward and reclaimed water could be a sustainable solution. Recycled water used for vegetative farming has to meet certain quality standards, thus additional technological tools such as chemical filtration and bio filtration are needed. In general, reclaimed greywater for agricultural use has high water supply expansion potential and rainfed irrigation is also feasible in-house for areas with sufficient rainfall.

5.2.3 | Informal settlements

In most developing countries, informal settlements are currently not part of a city's urban water management system. The lack of water supply facilities results in the informal settlers' reliance on self-fetched surface water, purchase of water from water kiosks and self-made unsustainable water systems. There are ongoing social challenges such as poor drinking water quality and incompetently built sanitation infrastructure. The greywater generated by them on-site would harbor germs and cause a hygiene-related disease burden to the congested-living communities. In areas with frequent rain, simple medium-sized rainwater tanks with gutter or umbrella harvester and filter systems could provide them with reasonably clean water for non-potable uses or even potable purposes with simple disinfection processes such as boiling or solar disinfection.

However, when it comes to decentralized greywater recycling, governance, the fragmented and fragile geography, lack of human resources (locally trained runners for maintenance services are lacking), in addition to the disadvantaged

BOX 1 Water literacy: Is it essential?

Literate environments are necessary to pursue water management sustainability, especially when it comes to the provision of potable water. Informal settlements are often correlated with poverty. Poverty is a wicked problem and tangled with other challenges such as lack of education and inequalities (Maniam et al., 2021). Moreover, the adaptation of water sustainability is effortful and time-consuming. The current roadmap for implementation of the SDG itself is planned over a 15-year period, while the Millennium Development Goals had been in place from 2000 to 2015. The same goes to behavioral change among the individuals to be more water literate, it is a long-winded commute. Any water supply and sanitation projects carried out in these localities or other areas should be followed by water education programs. This is because any unhygienic practice at the point-of-consumption would make the effectiveness and efficiency of water recycling procedure insignificant.

socio-economics of the local population obstruct the implementation of sophisticated technologies (Prescott et al., 2021; Putri, 2017). In this situation, the best practice is to adapt a modular onsite system, especially in areas with limited space, with locally available materials, and green infrastructure is a cost-effective option (Prescott et al., 2021; Putri, 2017). Phytoremediation technology using simple constructed wetlands aided with simple sediment and carbon filter are successful examples of decentralized systems adopted in many informal settlements such as Lima (Peru) and Machaki village (Pakistan) (Prescott et al., 2021). With a basic water piping infrastructure facility, decentralized greywater recycling could be done to produce water for mobile toilets too (Box 1).

6 | CONCLUSION

Anthropogenic activities have led to water stress in many parts of the world. With limited freshwater sources, reclamation of non-conventional water sources such as rainwater harvesting or greywater treatment and reuse provide a viable alternative to alleviate water stress. There are various technological options available to carry out rainwater harvesting or greywater treatment and reuse. A conceptual framework is proposed to provide an overview on the applicability of different technologies under various settings, mapped against usability of the treated water and the potential for water supply expansion. Decision makers could refer to the conceptual framework to decide on a suitable decentralized solution depending on limiting criteria. Decentralized systems of rainwater harvesting and greywater treatment for reuse are expected to play an important role to reduce the dependence on the centralized water supply, contributing to water supply for urban farming, and even to informal settlements.

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The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS
Geetha Maniam: Visualization (equal); writing – original draft (equal); writing – review and editing (equal). **Nur Ain Zakaria:** Writing – original draft (equal). **Leo Choe Peng:** Visualization (equal); writing – review and editing (equal). **Vasilena Vassilev:** Writing – original draft (equal); writing – review and editing (equal). **Karen Banahene Blay:** Writing – original draft (equal); writing – review and editing (equal). **Kourosh Behzadian:** Funding acquisition (lead); writing – review and editing (equal). **Poh Phaik Eong:** Conceptualization (equal); writing – original draft (equal); writing – review and editing (equal).

DATA AVAILABILITY STATEMENT
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