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The Potential of RainWater Harvesting Systems in Europe – Current State of Art and Future Perspectives

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Abstract

Water scarcity and climate change led to changes in water management, especially in urban areas. RainWater Harvesting (RWH) is a promising technique that allows the collection and reuse of rainwater, as well as protecting sewage systems from overload. This article reviews the current state of RWH in Europe, including advantages, implementation, potential efficiency, usage requirements, quality, and treatment processes. The main findings include the importance of RWH as a sustainable water management technique, the historical background and renewed interest in RWH systems in recent years, the positive impact of RWH on reducing energy consumption and greenhouse gas emissions, the versatility of rainwater usage, and the potential cost savings and benefits in various regions. RWH systems are gaining popularity in Europe, particularly in Germany, Austria, and Switzerland. Climate change and precipitation patterns affect rainwater availability and quality. RWH can be used for various purposes, including drinking, but requires proper purification for health safety. It is also being implemented in new locations like airports and large buildings. RWH systems have a high potential to overcome undesired results of climate change. Among that, numerous aspects still need to be considered in the future that allow the application of RWH systems on a larger scale.

Keywords Climate change · Rainwater harvesting · Rainwater quality · Rainwater treatment · Rainwater usage · Water demand

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1 Introduction

Historically, rainwater in European cities was considered a waste and hazard, and infrastructure was built to quickly remove it from building surroundings (Gimenez-Maranges et al. 2020). City growth and surface sealing exacerbated the issue and, as a consequence, stormwater drainage systems became more complex (Porse 2013). However, they can harm the ecosystem polluting incoming waterways severely and degrading the environment (Todeschini et al. 2014). Sealed surfaces lead to distraction in urban water cycle by decreasing the infiltration abilities and resulting in groundwater resources being difficult to recharge. Groundwater and surface water are inseparably linked (Banerjee and Ganguly 2023). Interactions between them are responsible e.g. for contaminant transport, and understanding it helps to estimate the effects of climate change, land use on chemical behavior, and the nature of water. Thus the understanding of their interactions is crucial for proper water management (Banda et al. 2023; Duque et al. 2023). More frequent intensive rainfall, related with climate change, enhance rapid surface runoff concentration (Kleidorfer et al. 2014; Hassan et al. 2017). The overlap of abovementioned factors results in cities being more prone both to urban flooding (excess water) and drought periods (water scarcity) phenomena (Mohammed et al. 2003).

Sustainable and resilient stormwater management is crucial. Low-Impact Development (LID) approach is nowadays recognized as a sustainable and economic solution to mitigate the negative impact of urbanization and climate change on hydrological processes, e.g. by restoring infiltration and runoff control (both peak flow and volume reduction) at the urban catchment scale (Liu et al. 2019; Singh et al. 2020; Castillo-Rodríguez et al. 2021; Cristiano et al. 2021; Ghodsi et al. 2021; Kaur and Gupta 2022). Rainwater is retained at the place of it occurrence. The LID structures relieve stormwater drainage systems, enhancing water infiltration and evapotranspiration processes (Palla and Gnecco 2022).

LID is also a solution for water scarcity issues. Overexploitation of water resources affects global food security and well-being. Only 2% of worldwide water resources are available to people. Importantly, water demand increased 6 times between 1990 and 1995. Agriculture accounted for about 70% of demand (Bwambale et al. 2022). Current water resources are scarce or seasonal. About 25% of the world's population has water-related health issues. Therefore, it is important to control microbiological and physico-chemical water characteristics. Population development, forest fires, and industrial expansion change rainwater chemistry. To improve its quality, treatment techniques must be implemented (Morales Rojas et al. 2021). Following treatment, rainwater can be used for potable purposes, including cooking and drinking, and non-potable purposes like flushing toilets, cleaning, and watering (Khan 2023).

Rainwater harvesting is not a new solution. Term "Water Sowing and Harvesting" was adopted from Latin America, where it involved gathering and infiltration (sowing) of rainwater, surface runoff, and groundwater to recover (harvesting) it later (Albarracín et al. 2021). This approach based on integrated water resources management and nature based solutions for water retention in aquifers. Promoting RainWater Harvesting (RWH), as an element of LID approach, is a promising way to reduce water scarcity and find an alternative water supply (Shanmugavel and Rajendran 2022). RWH systems become a viable economic and environmental option for populations without potable water (Akuffobea-Essilfie et al. 2020). There were grounds for the recent introduction of RWH systems to solve water scarcity: (1) humans use over half of freshwater runoff; (2) over 1 billion people lack access to clean potable water and almost 3 billion lack basic sanitation services; (3) the human population grows faster than freshwater recharge (availability per capita will decrease in the coming century); and (4) climate change will intensify water cycle. RWH systems can reduce resource use (Campisano et al. 2017), but their effectiveness depends on various factors: water demand, climate parameters, and sustainable design (Kapli et al. 2023). Cheap and cost-effective extended-operation RWH systems are essential for sustainability (Musz-Pomorska et al. 2020).

Although many research was undertaken on RWH utilization and effectiveness, many of them are case studies and are focused on specific aspects or presented with a high degree of generality. The information is scattered throughout many publications. The aim of the article is a systematic and comprehensive review of the RWH systems in Europe. The focus on this continent is related to the broad diversity of climatic, legislative, and socioeconomic conditions. The article covers various RWH aspects: utilization, factors affecting efficiency with climate change influence, implementation, limitations, application purposes, rainwater quality, and treatment processes. The innovation of the review lies in the synthesis of all these aspects in one paper, while these topics usually state separate publications.

2 Methodology

The work focused on reviewing the state of knowledge in 5 areas, presented in subsections:

- the implementation of RWH systems in Europe and reasons why these solutions have become attractive to society (Chap. 3.1),
- meteorological conditions that predispose European countries to effectively use rainwater and the impact of climate change on the RWH potential (Chap. 3.2),
- water supply purposes in which tap water is replaced with rainwater, requirements and limitations on its use (Chap. 3.3),
- characteristics and legislation regulating the rainwater quality (Chap. 3.4),
- rainwater treatment processes (Chap. 3.5).

The paper focuses on scientific articles in peer-reviewed international journals, published in English, mainly between 2000 and 2023, except for a few published before 2000 due to the relevance of illustrating previous approaches to the topic and trends. The common search engines were used: Google Scholar, Scopus, Microsoft Academic, ScienceDirect, Mendeley, and ResearchGate, as well as websites of the water-related journals. To isolate publications related to RainWater Harvesting, a 4-step process was used:
Step 1. A systematic literature review was conducted using keywords, citations, and related articles to identify relevant publications. A list of keywords used for subsequent subsections is provided below:

- Section 3.1: alternative water sources; rainwater purposes; water saving solutions; RWH: advantages, funding programs, implementation, RWH in Europe; RWH systems;
- Section 3.2: atmospheric circulation; climate change; hydrological factors; meteorological conditions; meteorological elements; precipitation patterns; water cycle;

- Section 3.3: rainwater in: cities, households, urban agriculture; rainwater outdoor uses; rainwater potable and non-potable uses; rainwater quality requirements; rainwater usage and limitations; RWH in airports; water consumption structure;
- Section 3.4 and 3.5: drinking water quality; rainwater: composition, compounds, contamination, disinfection, documents, filtration, legislation, ordinance, pollutants, pollution, purification, quality, treatment; water quality regulations.

Step 2. Reading abstracts for preliminary analysis and selection of publications found in Step 1 in terms of research topics. Papers not closely related to RWH, or in which the presented research was not conducted in Europe, were rejected.
Step 3. Analysis of full texts of publications selected in the previous step. The decision to include publication in the review was made considering the following questions:

- Is the article consistent with the topic of the work?
- Does the publication cover Europe?
- Do the methods described have practical applications?
- Is the article consistent with current trends?
- Is the data presented in the work up to date?

At this stage, publications cited in selected works were also checked.

Step 4. Final selection of publications. Information resulting from the review was organized in Sect. 3 of this review.

3 Review of the Current Knowledge State

3.1 RWH Advantages, Implementation Stage, and Funding Programs in Europe

RWH systems have a long history, described in many works (Fewkes 2012; Angelakis 2016; Yannopoulos et al. 2017). They were utilized less in the 20th century due to better supply technologies, but they are presently becoming more popular as a water source worldwide. Despite advancements in technology, providing clean drinking water remains a challenge worldwide due to increasing demand and depleting traditional sources (Lieste et al. 2007; Schets et al. 2010; Santos et al. 2020). These negative impacts are caused by unsustainable human activity, population increase, urbanization, and climate change (Che-Ani et al. 2009). Water supply systems often face long-distance water distribution issues (from water intake to the users). On hot days, when demand is high, the water supply will face one of their biggest challenges (Rak et al. 2021). In the event of waterworks failure or inefficient water supply wells, RWH systems provide an alternative source of water (Marlow et al. 2013), and sometimes may be even the principal source (de Sá Silva et al. 2022). RWH can reduce water stress and be an adaptation strategy to climate change (Hassell 2005; Yannopoulos et al. 2019).

RWH is not confined to water-scarce areas. Rainwater is free and decreases water companies' costs. Energy used to collect, purify, distribute, and store water accounts for most of these expenditures, e.g. in Germany it accounts for 1.71 kWh/m^3, and it is estimated that water supply systems use 7% of global electricity (Wakeel et al. 2016). Alternative water sources reduce tap water and energy use. However, RWH systems use electricity, therefore energy consumption is a key factor in assessing their profitability (de Sá Silva et al. 2022).

Due to reduced tap water consumption, RWH extend the lifespan of centralized water distribution infrastructure (Lopes et al. 2017; Viola et al. 2023) and can extend house devices life due to the purity of rainwater (Che-Ani et al. 2009). Many implementation manuals and design guidelines define local RWH system design configurations, including German (DIN 1989), British (British Standards Institute 2013a, b), Italian (UNI 2012), and French industrial standards (AFNOR 2011). RWH systems are cheap and easy to maintain. Users benefit from their modularity, which allows extension, reconfiguration, and transfer (Che-Ani et al. 2009), as well as from reduction of tap water bills, e.g.in a typical Slovak household it accounts for €225/year (Pavolová et al. 2019). RWH systems improve the state economy by reducing tap water use and water purification expenses (Vargas-Parra et al. 2013). Reduced environmental pollution, heat waves, and fine dust (Dallman et al. 2021; Nandi and Gonela 2022; Jin et al. 2023), reduction of new investments in aging or expanding urban water infrastructure, and expanding water infrastructure are other benefits (Lopes et al. 2017).

Rainwater should be also seen as a hazard that must be controlled. Urban floods, erosion, landslides, and unexpected surges undermine infrastructure due to severe rainfall. Climate change affecting air temperature and precipitation patterns, and increases flood frequency (Faragò et al. 2019; Hofman-Caris et al. 2019; Bieroza et al. 2021). Urban drainage systems typically cannot absorb climate-induced rainwater streams (Hussain et al. 2022; Kumar et al. 2022), but can be relieved through rainwater collection, which makes RWH a strategy for minimizing the flood risk and surface water quality degradation (Palla et al. 2017; Stephan and Stephan 2017). New research has examined the application of RWH systems to reduce soil erosion (Jiang et al. 2013), urban runoff volumes and peaks (Malinowski et al. 2015), urban drainage system pressure and electricity demand (de Sá Silva et al. 2022).

Proper rainwater management reduces dry conditions and boosts resilience. Technical, economic, and social innovations are needed (Musz-Pomorska et al. 2020). RWH systems improve water use and energy efficiency (water-energy nexus), and bring environmental and social advantages (de Sá Silva et al. 2022). However, these systems need government actions to make them financially attractive (Wanjiru and Xia 2018) and numerous European governments begun legal or subsidy schemes to promote RWH, similarly as the EU (Campisano et al. 2013). RWH implementation and technology selection depend heavily on local rules, and varies between European countries (Campisano et al. 2017; Musz-Pomorska et al. 2020). Scientific literature also shows growing interest in RWH systems - in 2017, 57% of publications about rainwater collection were published in Europe (Morote et al. 2020).

Germany is one of the leaders in the RWH systems use and research. The concept of using rainwater appeared in 1970–1975 due to management issues with water supply and sewage systems (Fewkes 2012). It evolved in the 1980s with the focus on low impact development technologies (García Soler et al. 2018). In the 1990s, the conceptualization of combining several decentralized rainwater management techniques appeared, which is now the approach being a mandatory element of integrated storm water management (DWA 2016). Rainwater must be kept on site whenever possible under German water law (Fletcher et al. 2015). RWH systems became popular because urban drainage fees are based on impermeable property surfaces - disconnecting roofs from the sewage system is profitable (Herrmann and Schmida 2000). Around 75,000 RWH systems are installed in Germany each year, and 2/3 of newly built homes have them. Property owners only need to notify water supply companies about construction, no authorization is needed. Bremen subsidize RWH installation at 1/3 of the cost of residential RWH. Thuringia offers residential property program loans up to EUR 5,000. Saarland and Schleswig-Holstein both provide subsidies (Schuetze 2013).

For climate change adaptation, the Netherlands has set policy goals to increase urban water retention capacity. The first Water Plan (2001), Water City 2035 (2005), the transformation to the second integrated Water Plan (2007), the Rotterdam Climate Proof Program (2008), the Rotterdam Adaptation Strategy (2013), the Resilience Program (2014), and the Water Sensitive Rotterdam Program (2015) are programs related to the water management vision in Rotterdam. Rotterdam Water City 2035, a non-official policy approach produced by urban planners and urban water experts, is noteworthy (de Graaf and der Brugge 2010).

Great Britain also protects water resources. The 2008 Future Water Program (DEFRA 2008) aimed to cut tap water use to 130 L per person per day by 2030. It is achievable when using rainwater for flushing toilets or watering plants. About 7,500 residential and commercial RWH systems were installed in 2011 (Fewkes 2012). There is no regulation in the UK for them, but there is a code of practice (BS 8515:2009) for system design, installation, maintenance, water quality, and risk management (Ministry of Housing 2009).

RWH systems are not well-developed in other European countries. Italian researchers studied rainfall efficiency for rainwater use (Paciarotti, C.; Ciarapica, F.E.; Giacchetta; Liuzzo et al. 2016). The main obstacles to RWH system development in Italy were consumer reluctance and lack of design guidelines. Several Spanish towns mandate RWH system installation for new buildings with gardens (Domènech and Saurí 2011; Campisano et al. 2017). France imposed legal regulations in 2008 (now withdrawn) and a tax relief (Article 49 of the Water Act of December 30, 2006). RWH was used in sustainable urban development systems in a former big industrial and port area in southern Stockholm (Campisano et al. 2017). In Flanders (Belgium), new buildings with roofs over 100 m^2 must have RWH systems (De Gouvello et al. 2014). RWH is also becoming popular in Austria (Knoll et al. 2021), Switzerland, Denmark, and Poland (Carollo et al. 2023; Viola et al. 2023), where the main factor in RWH system development is the price of tap water (Campisano et al. 2017).

3.2 Meteorological Conditions in Europe – RWH Efficiency Potential

Climate change threatens water supply worldwide by changing meteorological variables (precipitation patterns, air temperature, humidity), affecting extreme weather events and heatwaves. RainWater Harvesting has been studied in susceptible places to improve community resilience to unexpected weather and climate change affecting water availability. The intricate interactions of air circulation, precipitation patterns, and climatic fluctuations affect European RWH systems. Exposure projections show substantial hazard scenarios, especially those associated with rising temperatures and geographical patterns largely regulated by local climate (Forzieri et al. 2016). European heatwaves and precipitation patterns are affected by the NAO and atmospheric blockage. The NAO phase index, in particular, has been associated with changes in precipitation distribution, e.g. with NAO positive, unrelated events leading to increased precipitation and cold air in the southern part of Europe, resulting in high temperatures contracting to the northern part of Europe (Li et al. 2020).Variations in regional air circulation across Europe during the Last Glacial Maximum affected precipitation patterns in Southern, Central, and Eastern Europe (Ludwig et al. 1955). Long-term variations in seasonal rainfall patterns in Europe have been connected to dynamics, highlighting the complex interaction between meteorological dynamics and precipitation patterns (Hoffmann and Spekat 2021). From the 1960s to 1990, synoptic weather patterns decreased anticyclonic and increased cyclonic, decreasing solar irradiance variability in Northern Europe (Parding et al. 2016). The need to understand and anticipate atmospheric circulation and precipitation patterns is also underscored by uncertainties in estimating future atmospheric river changes and their effects on heavy precipitation across Europe (Gao et al. 2016). Northern Europe has seen a 10–40% rise in rainfall, while Southern Europe has seen a 20% decline. This could lead to a decrease in drinking water availability in Southern Europe, affecting water resources (Senent-Aparicio et al. 2017; Dezsi et al. 2018; Gwoździej-Mazur et al. 2022).

Understanding how climate change affects RWH in Central European households, is crucial. Summerville and Sultana (Summerville and Sultana 2019) discovered that household RWH in 46 European cities can save 20–100% of non-potable water, depending on climate zones. Rainwater quality is affected by shifting European precipitation patterns. The health dangers assessment related to rainwater obtained from different rooftops has emphasized the need for a rigorous inquiry to determine the true effects of continuous rainwater consumption and alternative solutions (Hamilton et al. 2019; Osayemwenre and Osibote 2021; Juiani et al. 2023). These studies reveal the practical ramifications of RWH systems under varied meteorological circumstances and their efficiency in regulating precipitation outside Europe, making this topic global.

3.3 RWH as an Alternative Water Source, Requirements, and Limitations

RWH systems collect rainwater generated from roofs, terraces, and courtyards during rainfall events and store it in reservoirs to meet water demands for various uses (Zhang et al. 2019; Teston et al. 2022; Jegnie et al. 2023). Households use 10% of EU water for hygiene, flushing toilets, washing, cooking, watering gardens, and other cleaning activities (EEA 2017). The majority of tap water (62%) is used for hygiene and toilet flushing. Detailed water use structure in selected European countries is given in Online Resource 1. Water consumption purposes can be divided into potable and non-potable uses. In the first scenario, water must meet strict quality standards because it has contact with humans and may harm them. Potable uses include drinking, cooking, and hygiene. Due to no human contact, the water may be lower quality in the second situation. These include toilet flushing, laundry, cleaning, car washing, and garden watering (Antunes et al. 2020).

Rainwater replaces tap water for non-potable and potable uses worldwide (Campisano et al. 2017; Zhang et al. 2019). Depending on meteorological circumstances, RWH systems in residences can save 12–100% tap water. RWH is mostly pushed in wealthy nations like Belgium, France, and Germany to supplement non-potable uses including toilet flushing, clothes washing, outside washes, and irrigation (Silva et al. 2015). Still, using rainwater just for toilet flushing can cut tap water use by one-third for an average family (Nolde 2007; Campisano et al. 2013). Rainwater is eagerly used for home applications due to its often better properties in terms of composition compared to hard tap water (Sklenárová 2011):

- effective dissolution effects (perfect for laundry, washing floors, cleaning),
- no minerals (suitable for window cleaning or car washing – leaving no white patches),
- no aggressive chlorine,

- warmer (suitable for watering plants),
- soft (does not form limescale),
- behaves similarly to distilled water.

In certain nations, rainwater is only used for non-potable purposes due to industrial air pollution and severe water quality laws, e.g. according to The Netherlands' water regulations (Schets et al. 2010) household rainwater can only be used as gray water for flushing toilets (a consequence of hundreds of people getting sick from low-quality home water due to drinking water and rainwater networks cross-connection). The standards warn of the danger of infection from gray water exposure – it should be less than one infection per 10,000 persons yearly. No worldwide standard governs potable or non-potable rainwater quality. In Germany, the DIN 1989 standard allows rainwater to be used without restrictions for non-potable purposes. Simultaneously, the German Drinking Water Act requires using tap water for washing (Schuetze 2013). The DL 23/95 in Portugal limits the use of non-tap water to pavement washing, irrigation, firefighting, and nonfood-related industrial production. Rainwater cannot be used for drinking or personal hygiene in France (Vialle et al. 2015).

Rainwater is used for outdoor purposes (Sample and Liu 2014; Zhang et al. 2019): watering lawns and gardens, composting, washing vehicles and equipment, fire protection, outdoor ponds, swimming pools, cleaning the exterior of buildings. Plants develop better when watered with rainwater (as being chlorine-free and salt-free). Plants grow faster by developing larger root system and become less sensitive to droughts by reducing salt accumulation in the soil (rainwater "moves" salts away from the root zone) (Che-Ani et al. 2009; Salehi-Lisar and Bakhshayeshan-Agdam 2016). Although there is limited study on using rainwater for urban agriculture, it can be used to grow food in the city (Hume et al. 2022). In Antalya, where half of Turkey's greenhouses are located, RWH systems may cover plant needs (Ertop et al. 2023). Recently, green roofs and rain gardens have gained popularity due to improving urban microclimate. They require water for maintenance and using harvested rainwater saves water and cools the urban heat island (Fewkes 2012). The research on rainfall-runoff relation between green roof and RWH system in Paris has been investigated (Xie et al. 2023).

Rainwater is frequently collected in office buildings, which utilize approximately 50% of the water for flushing toilets (Griggs, J.C., Shouler, M.C.; Hall 1997). RWH systems for flushing toilets has high water savings efficiency, varying between 0.6 and 100% (depending on rainfall) (Ward et al. 2012; Yan et al. 2018). Research results proof that commercial buildings can meet water demand with rainwater. The literature discusses using RWH in educational buildings, where the highest potential for potable water savings was 53.2% (Teston et al. 2022), and in hospitals, where 20–30% water savings are estimated, but these few studies were conducted in a semi-arid region (Fulton 2018). Another article discusses the RWH system designed for a sewage treatment plant near Mirandela (Portugal) to wash vehicles, equipment, clean concrete and asphalt surfaces, and water greenery (Sanches Fernandes et al. 2015). Similar research was undertaken in the South of Portugal, where a substantial potential for the feasibility of RW systems in retail stores has been proven (Ferreira et al. 2023).

Airports may require as much water as medium and big towns (equal to a city of 30,000–34,000 people). Nearly 65% of airport water demand does not require tap water quality: air cooling, irrigation, aircraft and hard surface washing, fire protection, and toilet flushing. The rainwater replacement rates depend on the purpose of usage (Blokker et al. 2011): terminals and offices had the highest factor of 0.7 due to toilet flushing's large contribution of water use; hangars and cargo buildings amounts to 0.5, and hotels to 0.1 (the lowest value) due to utilizing water for hygiene and cooking. Airports may collect more rainwater than households due to their huge roofs (Jaiyeola 2017). Among European airports with RWH systems, following can be listed: Frankfurt International, Orly and Charles de Gaulle, Brussels International, Heathrow, Zurich. Only a few studies have examined RWH's potential at airports. RWH system was considered for Manchester Airport, for non-potable uses including road sweepers and fire training (as of 2007) (Carvalho et al. 2013). Rainwater might replace 58% of Schiphol airport's non-potable water demand while being stored in five empty jet fuel silos (Kuller et al. 2017), but the long payback period (30-year) makes it uneconomical.

Rainwater quality criteria vary by use. If consumed, it must fulfill drinking water standards. WHO, EPA, and EU have issued such guidelines. WHO established drinking water quality standards (WHO 2022) and regulates physicochemical and microbiological factors to ensure that water is safe to drink. These inspired other nations to pass WHO-based laws. However, EPA prepares reports on water contaminants. To preserve water resources from agricultural pollution, the EU has passed significant laws. The Drinking Water Directive (DWD) of Council Directive 98/83/EC (and its modification EU 2015/1787) was the basis for state-level regulation in Europe. When water distribution systems serve more than 50 people or produce more than 10 m^3/day, water quality analysis is required. However, the regulation does not apply to families and small water treatment plants. The option of creating water from different sources is also ignored. The Drinking Water Directive warns consumers of the dangers of contaminated water and ensures clean drinking water (Morales-Figueroa et al. 2023). Regulation of the Minister of Health of December 7, 2017, on the quality of water meant for human consumption sets Polish quality standards. The document specifies physicochemical and microbiological parameters, and also sampling technique and frequency. The document controls ion concentration, pH, conductivity, color, and turbidity. For microbiological parameters, regulate *E. coli*, coliform bacteria, *Pseudomonas aeruginosa*, and *Legionella*.

The WHO Joint Monitoring Program calls rainfall an "improved" water source and stresses the need to prevent fecal bacteria contamination. The program covers small and large drinking water sources. However, the law should also cover other drinking water sources. Water quality and safety must be updated. Proposal EC COM 753/2017 on the quality of water intended for human consumption, EC Best Environmental Management Practice in the Tourism Sector, Harvesting Rainwater for Domestic Uses: An Information Guide (Environment Agency), European Commission, 83/1998 EC DWD also cover rainwater use and drinking water quality.

3.4 Rainwater Quality

3.4.1 Factors Influencing the Quality of Rainwater and Sources of Pollution

Rainwater reactivity is neutral, its hardness is minimal, and disinfection byproducts are absent compared to groundwater or surface water. However, it absorbs contamination upon contact with the ground. The quality of collected water is influenced by the following factors (Abbasi-Garravand and Mulligan 2014):

- characteristics of atmospheric phenomena (intensity, duration, wind speed),
- meteorological factors (seasons, duration of no-rainfall period, weather characteristics),
- pollutants concentration in the atmosphere,
- roof material, location, geometry, substances present on the surface (polarity, solubility, Henry's constant), and maintenance works.

Many organic and inorganic substances in the air react with water. In rural areas, rainwater mainly contains dissolved gasses, while in highly urbanized areas anthropogenic influences are visible. Rainfall intensity and duration greatly affect rainfall quality (Willey et al. 2011; Ortega Sandoval et al. 2019). Wet deposition washes off 90% of atmospheric microbes, heavy metals, and organic compounds during rainfall. Water that had not touched the surface had little metal content – mainly calcium, potassium, and sodium, less often copper, zinc, iron, sulfates, and phenols. Their presence is mostly caused by transport and fuel combustion pollutants (Hofman-Caris et al. 2019; Jose and Heidy 2022).

Research (Zdeb et al. 2020) confirms the influence of the roof material on pollutants found in collected rainwater revealing differences quality of water collected from roof surfaces and collected directly from rainfall. Roofs made of copper, zinc, or covered with paints with metal admixtures may be a source of heavy metals and it is not recommended to collect water from their surfaces. Steel surfaces absorb less atmospheric particles than asphalt surfaces, allowing for high-quality rainwater collection. Wooden shingles also encourage lichens and mosses, which raise total organic carbon (TOC), nitrates, and sulfates. The roof surface roughness influences the water turbidity and concentrations of nitrogen and phosphorus compounds. The sources of organic compounds may be bird droppings, plant pollen, spores of fungi and bacteria, or bryophytes and lichens growing on the roof. To limit the secondary development of microorganisms, rainwater parameters should meet the stability criteria: the concentration of biodegradable organic carbon below 0.25 mgC/L, the sum of inorganic nitrogen concentrations below 0.2 mg/L, and phosphates below 0.03 mg/L. The collected water is microbiologically clean when the roof is galvanized steel and the worst quality is for epoxy and concrete roof surfaces. The season affects microbiological quality: rainwater had the best quality in fall, and the poorest in summer (Raimondi et al. 2023). Investigations of the dependence of the rainwater quality on different collection surfaces (roof covered with felt, "blue roof" covered with felt and gravel fraction, and parking) is presented also in (Mazurkiewicz et al. 2022).

Rainwater harvested from roads may contain heavy metals released from tires or brakes and organic polycyclic aromatic hydrocarbons generated during incomplete combustion processes. The type of storage tank used can also affect the properties of the water – plastic tanks may give rainwater slightly acidic properties and concrete tanks – alkaline. There is a risk of bacterial, viral, and protozoan contamination from the excrement of animals that enter to the tank. Therefore, it is recommended to test for bacteria, enterococci, and *E. coli* (Gromaire et al. 2002; Helmreich and Horn 2009). Typical rainwater components and their source can be classified as (Mosley 2005):

- dust and ash – surrounding dirt and vegetation, volcanic activity;
- pathogenic bacteria – bird and other animal droppings on the roof and attached to dust;
- heavy metals – dust, particularly in urban and industrialized areas, roof materials;
- other inorganic contaminants – seaspray, industrial discharges to air, tank/roof materi-

als;
- mosquito larvae – mosquitos laying eggs in guttering and/or tank.

3.4.2 Research Conducted on the Quality of Rainwater in Europe

Many research were undertaken across Europe regarding rainwater quality. Research (Keresztesi et al. 2019) presented data on the rainwater quality from 27 European countries in years 2000–2017. It was observed that in most cases the share of individual ions in the tested waters was in the following order: SO_4^{2-}> Cl^- > Na^+>NH_4^+>NO_3^-> H^+> Ca^{2+}> Mg^{2+}> K^+> HCO_3^-. In all countries, the dominant ion was the sulfate anion with content varied from 40.60 mval/L (in Spain) to 48.38 mval/L (in Lithuania). In the case of cations, the Na^+ ion dominated. The pH value of rainwater was between 4.19 and 5.82. The pH of rainwater in an unpolluted atmosphere at equilibrium is 5.6, values below this level are considered acidic. In Central Europe, both the lowest and highest pH values (4.56 and 5.33, respectively) were recorded in Belarus. In Northern Europe, the precipitation was more acidic, with the lowest (4.47) and highest (5.15) pH values found in Estonia and Great Britain. The obtained pH values indicate a significant impact of anthropogenic activities, but also natural factors: sea aerosols, volcanic activity, biogenic materials, and dust on the ground as a result of the weathering process. Main research findings emphasize that in Europe particular ions in rainwater come from: the sea (Na^+ and Mg^{2+}), biomass combustion (K^+), soils and weathering processes of limestone and dolomites (Ca^{2+}), anthropogenic sources (SO_4^{2-} and NH_4^+), and road transport (NO_3^-).

It should be emphasized that the distribution of pollutants was relatively uniform, which is related to uniform laws and standards introduction regarding environmental protection. Uniform regulations enable comparison of the values obtained in tests with European standards for drinking water quality. According to many works related to rainwater quality research, it was decided to describe in detail only few of them, and the broader rainwater characteristics from research are attached in Online Resource 2.

Rainfall quality studies conducted in industrial areas (nickel, cobalt, and copper production and apatite mining) in the Arctic region of Northern Europe (Reimann et al. 1997) showed the presence of 38 heavy metals in collected rainwater, with clearly increased concentrations of calcium, chlorine, sodium, copper, cobalt, nickel, molybdenum, iron, magnesium, and strontium. Rainwater has low pH of 3.7–6.5 and an electrical conductivity of 0.4–9 mS/m. Exceedances were found for contaminants related to the Barents Sea proximity: Cl^- and Na^+.

Rainwater quality in France was tested in the period 1995–2007 (Pascaud et al. 2016). Analysis of the ion content showed seasonal variability – 21 mval/L in winter and 37 mval/L in summer, which is related to the intensification of photocatalytic reactions in the summer season. The usage of large amounts of contaminated coal resulted in an increase of SO_4^{2-} content in winter compared to the summer season. Over the years 1995–2007, the average sulfates concentration in rainwater was reduced by 30%, the nitrates concentration remained constant (reduction only in some areas), and ammonium concentration had a decreasing trend. The reduction of sulfates, nitrates, and ammonium is probably related to the application of legal regulations on the emission of these compounds into the atmosphere. The ammonium ion content reached the highest value (42–46 mval/L) in seasons with higher temperatures, probably due to the release of ammonia into the atmosphere from fertilizers.

The occurrence of bacteria in rainwater is a matter of concern because of people's exposure to diseases and is increasingly discussed in research, also in France (Vialle et al. 2011, 2012). The amount of psychrophilic bacteria (22 °C) was 10 to $6.32 \cdot 10^5$ organisms/ml, higher than mesophilic bacteria (36 °C). *E.coli* was found in 79% of samples, and enterococci sometimes exceeded 10,000 colony forming units (CFU)/100 ml. *Aeromonas* bacteria (43%), *Pseudomonas aeruginosa* (41%), and *Legionella pneumophila* (700 CFU/L) were also found in the water. Similar results were obtained in other work (Fewtrell and Kay 2007).

Several studies on rainwater quality have been carried out also in Poland. The statistically significant downward trend in the pollutant load from precipitation was observed (IMGW-PIB 2023). Measurements for 2022 revealed a total surface load of 31.97 kg/ha/yr, lower by approximately 33% than the average value for the period 1999–2021. Compared to 1999, the country's area load was lower by over 50% (Fig. 1).

Research was conducted also in protected areas (National Parks). In the Tatra Mountains (Małecki et al. 2022) pH increased from 5.22 to 5.95 in years 2002–2019 and was higher than for years 1993–1994, when pH reached 4.39. Electrical conductivity fell from 15.2 to 10.4 µS/cm (comparing to 32.71 µS/cm in the 1990s). These trends confirm the air quality improvement during the period. Sulfates, nitrates, calcium, chloride, sodium, and ammonium nitrogen concentrations reduced with time. Magnesium and potassium levels rose. Research conducted in Roztocze National Park (Grabowski et al. 2023) revealed high turbidity (up to 6.7 NTU) and conductivity (up to 84.64 µS/cm). High concentrations of bacteria in the samples, reaching 70 CFU/100 ml for *E. coli* and 120 CFU/100 ml for enterococci were also obtained.

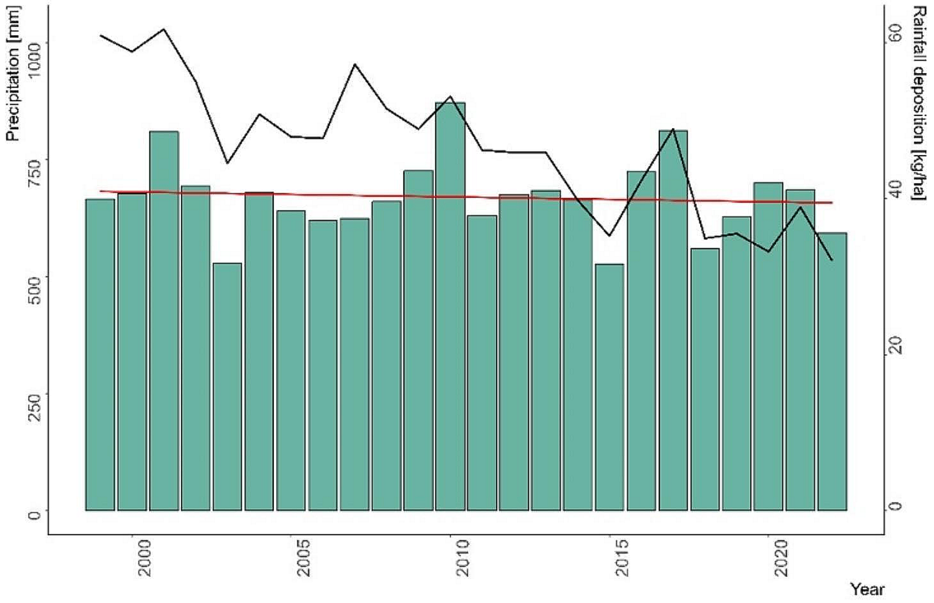

Fig. 1 Average annual deposition and annual rainfall in years 1999–2022 (IMGW-PIB 2023)

Pavolova et al. (Pavolová et al. 2019) tested rainwater quality in Slovakia. The pH ranged between 6.5 and 8.4. The dissolved substance content did not exceed 118 mg/L. Rainwater had low calcium and magnesium levels. No metals (Ni, Zn, Hg, Fe, Al, Pb, and Cr) were found.

Rainwater quality was tested in significant mining and industry areas (mainly steel and machinery) in south-eastern Romania (Keresztesi et al. 2020). The average pH values ranged from 6.18 to 7.06 showing the acidic nature of rainwater. It was shown that lower-intensity rainfall usually carried a higher pollutant load. In two of the three areas, the ion content in rainwater showed a similar order: $Ca^{2+} > SO_4^{2-} > Mg^{2+} > Cl^- > NH_4^+ > HCO_3^- > K^+ > Na^+ > NO_3^- > NO_2^- > H^+$, with the dominant cations were Ca^{2+} and Mg^{2+}, the large share of which may have resulted from the mining processes of calcite and dolomite rocks ($CaCO_3$ and $MgCO_3$). The largest share of over 43% in the total sum of all collected anions had SO_4^{2-}. In the last studied area, the concentration of ions in rainwater was in a different order in terms of their concentration: $Cl^- > Ca^{2+} > NH_4^+ > Mg^{2+} > SO_4^{2-} > Na^+ > HCO_3^- > NO_3^- > K^+ > H^+ > NO_2^-$. The dominant cations were Ca^{2+}, NH_4^+, Mg^2+, which accounted for almost 84% of the total sum of cations, while the dominant anion was Cl^-, constituting over 58% of their mass. The highest heavy metals concentrations were detected for Pb and Cd, and significantly lower for Ni and As. Another research on rainwater quality can be found in (Arsene et al. 2007).

Research conducted on the Black Sea coast (Alagha and Tuncel 2003) showed low pH values of rainwater, corresponding with high concentrations of SO_4^{2-} and NO_3^-, indicating its acidic nature. Most precipitation events with a pH value below 5 occurred in winter due to burning fuels and coal. A high share of Cl^- and Na^+ ions was demonstrated, indicating a large share of marine waters in precipitation.

Orlovic-Leko et al. (Orlović-Leko et al. 2020) analyzed the quality of rainwater in Croatia. The concentration of dissolved organic carbon (DOC) reached 0.69–4.86 mg C/L, whose origin was mainly related to road transport and the operation of thermal power plants using various types of fuels. These contents are comparable to the results obtained during studies in 1998–1999 (0.78–4.39 mg C/L) and 2003–2007 (0.67–4.03 mg C/L) (Leko et al. 2004). The highest values of heavy metals occurred for Al and Fe, 569.4 and 405.8 µg/m^{2}d, respectively, as well as for Cr, Zn, Ba, and Mn (20–40 µg/m^{2}d). The lowest fluxes ($<$0.4 µg/m^{2}d) were found for Se, Cd, Co, and Mo. The combination of Zn and Co with typical geological markers (Al, Fe, Sr, Ti) suggested that they entered rainwater along with dust lifted from road surfaces. Mo and As were most correlated with Cu, indicating generation during fuel combustion.

Research results on rainwater quality in Greece (Sazakli et al. 2007) indicated the pH above neutral ranging of 7.63–8.80 and low conductivity $<$ 220 µS/cm. The concentrations of sodium ranged from 2 to 11 mg/dm^3 and from 3 to 16 mg/dm^3 for chlorine ions. The tests showed high concentrations of $CaCO_3$ (from 24 to 74 mg/dm^3). Seasonal variability of ion content and conductivity was demonstrated, higher in winter compared to other periods. Microbiological quality tests detected coliform bacteria in over 80% of samples, with *E. coli* bacteria detected in 40.9% and enterococci in 28.8% of the samples.

In Aveiro (Portugal) research conducted in 2009 were compared to results obtained in 1986–1989 (Santos et al. 2011). The significant predominance of chloride ions is related to the close location of the Atlantic Ocean, with a comparable level over the years. The concentrations of ammonium ion and nitrates in winter were lower compared to other ions.

Over the past 20 years, an increase in the content of nitrogen compounds has been observed, which is related to the development of transport and industry, and a decreasing trend in the sulfur ion content, which may be the result of a decrease in the sulfur content in diesel fuels.

Quality of rainwater depending on the collection surface was conducted in Barcelona (Spain) (Farreny et al. 2011; Angrill et al. 2017). The main findings are as follows:

- the worst quality was observed for asphalt promenades and parking lots (the highest values of chemical oxygen demand (COD), NO_3^-, HCO_3^-, PO_4^{3-} and SO_4^{2-});
- for concrete surfaces high concentrations of chlorine and iron were found (related to the use of salt in winter and the corrosion of metal parts);
- a higher concentration of organic matter and lower concentration of ammonia was detected in rainwater from ground level than from roofs;
- the microbiological rainwater quality did not differ between surfaces and is comparable to the quality of surface- and groundwater;
- rainwater had similar total suspended solids for different materials (only metal roofs with slightly lower values);
- the highest TOC values were found for a gravel roof (up to 53.6 mgC/L), and the lowest values (< 10 mgC/L) for sheet metal and polycarbonate;
- clay and gravel roof samples demonstrated higher conductivity than metal and polycarbonate roof samples, ranging from 15.4 to 456 µS/cm;
- the highest or significantly higher concentrations of ions (SO_4^{2-}, NO_2^-, NO_3^-, NH_4^+, PO_4^{3-}, Cl^-, and total carbonates), in almost all cases were found for water collected from a gravel roof, apart from NH_4^+, for which a gravel roof showed the lowest concentration and sheet metal and polycarbonate – the highest.

Experiments on the composition of rainwater were also carried out in Turkey (Guzel 2021). The pH of the samples ranged from 5.81 to 7.27. The electrical conductivity varied between 22.1 and 126.2 uS/cm. The content of ionic substances was arranged as follows: $Ca^{2+} > Na^+ > SO_4^{2-} > Cl^- > Mg^{2+} > NO_3^- > NH_4^+ > K^+ > PO_4^{3-} > NO_2^- > F^-$. The sampling site was located close to the coast and forests, but also to an industrial area, so the contaminants' origin were both natural and anthropogenic sources. The average content of ions was as follows: calcium 470.6 mg/L, sodium 133.8 mg/L, sulfates 116.2 mg/L, chlorides 94.0 mg/L, magnesium 82.8 mg/L, nitrate 57.9 mg/L, ammonium 39.2 mg/L, potassium 20.9 mg/L. Phosphates, nitrites, and fluorides had the lowest content (17.7, 14.3, and 1.6 mg/L, respectively). Among the trace substances present were: Al (34.52 µg/L)>Fe (26.03 µg/L)>Ba (20.67 µg/L)>Mn (18.06 µg/L)>B (16.39 µg/L)>Sr (16.27 µg/L) L)>Cu (10.42 µg/L). The concentration of these substances was higher in the spring (dry) season than in the winter (wet) season, and was the result of industrial activity and road works. The average TOC content was 1.38 mg/L.

3.5 Rainwater Treatment Technologies

3.5.1 Rainwater Treatment Processes

The presence of pollutants in rainwater requires its purification before use. Rainwater treatment uses physicochemical techniques to remove colloids, suspended particles, and microbes. Natural materials like adsorbents and microorganisms are also used to remove heavy metals, organic matter, and nutrients. Solar radiation-based oxidation kills microbes. These methods are generally used with more common processes. Table 1 summarizes the currently used rainwater treatment processes.

Filtration removes certain dissolved solids and solid particles from water, lowering water turbidity, color, and microbes. Mineral and organic particles like activated carbon (AC), crumbled bricks, and coconut fibers can filter even dissolved pollutants. Zeolites' porous structure and slow sand filters allow for physical and chemical pollutants removal (Muktiningsih and Putri 2021). Slow filters consist of a layer of sand and gravel and remove heavy metals, protozoa, and germs from rainwater, but odors poorly. Filtration by granulated AC bases on adsorption and removes color, turbidity, and organic matter at a low cost and without toxicity. It does not remove germs and viruses from rainwater, therefore UV radiation is needed when rainwater is intended for drinking purposes (Silva Vieira et al. 2013).

Membrane processes are also used for rainwater treatment (Raimondi et al. 2023):

- microfiltration (MF) – mostly used; removes only big organic compounds and pathogens; demands low transmembrane pressure;
- ultrafiltration (UF) – removes colloids, suspended contaminants, and microorganisms; low separation efficiency of oily substances and heavy metals and fouling are main drawbacks;
- nanofiltration (NF) – removes 99% organic matter and sulfates;
- reverse osmosis (RO) – removes 99.9% of pathogens, dissolved and colloidal contaminants; the installation requires frequent cleaning; fouling reduces filtration effectiveness, raises operating pressure, and shortens membrane life;
- forward osmosis (FO) – mentioned in literature, but rarely used.

Biological approaches are paired with physical or chemical procedures. No need to dose extra chemicals, reduced energy usage, and easy process execution are the main advantages. Bacteriophages like *Bdellovibrio bacteriovorus* can help lower the quantity of gram-positive bacteria by feeding on them, and reducing fouling (Kim et al. 2007) (Reyneke et al. 2020). Eventually, certain microbes develop bacteriophage resistance, reducing purification efficacy. Biofiltration involves filtering water through a biological bed. The bed's biofilm removes bacteria from the water and works well as a preliminary therapy. Bioretention uses additive-modified highly permeable sand and local soils. It removes suspended particles, lipids, and heavy metals. These methods do not remove COD, phosphate, nitrogen, or microorganisms. Biofilters can remove 98% of ammonium nitrogen, but high rainfall intensity reduces its removal efficiency. Biosorption materials like agricultural and food waste can also be used for water filtration. They are inexpensive, non-toxic, and readily available (Morales-Figueroa et al. 2023).

3.5.2 Research on Rainwater Purification Processes

The potential of a rainwater treatment system including filtration and disinfection was estimated in (Adler et al. 2011). Rainwater went through the sedimentation tank, the filtration chamber, the silver ion-generating unit, and finally – a combined filter with AC and a Kinetic Degradation Fluxion bed. The bacteria reduction amounted to 62.5–99.9%. The

Table 1 Processes applied in rainwater treatment (Lakshminarayana 2020; Liu et al. 2021)

Method	Function	Additional remarks
Chlorination	Inactivation and destruction of bacteria.	• Physicochemical parameters of rainwater (particularly turbidity) determine disinfection effectiveness.
UV radiation	Interference with microorganisms' DNA leading to destruction and multiplication inhibition.	
Membrane filtration	Dissolved solids removal.	• High energy consumption. • Fouling lowers membrane hydraulic performance. • Preliminary water treatment is required. • Specific membrane materials may improve the process: - metal membranes – resistant to pressure, temperature, chemical oxidants, better durability than polymeric membranes, effective in bacteria removal; expensive, - hydrophilic ceramic membranes – high purification effectiveness, good chemical oxidant resistance, antifouling properties; expensive. • Gravity flow membranes may reduce energy usage.
Pasteurization by solar radiation	Killing bacteria present in water (high effectiveness for *E. coli*).	• A highly effective method. • Allows to purify a small volume of water. • Increases the effectiveness of chlorination. • Depends on the intensity of solar radiation. • High water turbidity reduces the process effectiveness. • When PET tanks are used, toxic substances may be released. • Exposure to 500 W/m^2 sun light for 6 h eliminates almost all coli bacteria (De Kwaadsteniet et al. 2013).
Filtration through a granular bed	Removal of dissolved solids and solid particles by physical interaction of water with granular bed. It lowers water turbidity, color, and microbes.	• Rainwater filters must meet certain criteria (Abbasi-Garravand and Mulligan 2014): - easy to clean or self-cleaning, - not easily blocked by pollutants, - no leaching of other compounds. • Filter size, shape, and porosity affect process efficiency.
Activated carbon filtration	Effective removal of inorganic impurities (e.g. chlorine, mercury).	• Granulated activated carbon (GAC) mixed with zeolites or sand may remove over 90% of lead and ammonium nitrogen, 59–85% of turbidity, and >20% of COD and TOC.
Slow filtration through the sand bed	Water turbidity decrease and microorganisms removal.	• An economically rational technique. • Not effective in turbidity and microorganisms removal. • Simple structure. • Low operating costs. • Easy scalability for rural and small communities. • May reduce turbidity by 95%. • High turbidity reduces efficiency and shortens filter life.
Oxidation	Introduction of a strongly oxidizing factor, e.g. free radicals to rainwater.	• Advanced oxidation eliminates water germs (e.g. *Klebsiella pneumonia*) by 51–100% by direct sun exposure. • Radiation may increase hydroxyl radical generation, which causes cell lysis (Morales-Figueroa et al. 2023).
Electrocoagulation	Utilizing a chamber and a pair of electrodes to destabilize molecules with an electric field. Removes solutes, suspensions, and emulsions.	• Easy to conduct. • Solar panels can power the process. • Suspended solids can be removed by precipitation or flotation. • The technology allows to control of the volume of the formed sediments.
Membrane bioreactor	Production of water with good quality.	• High risk of fouling and high aeration costs. • Usage in rainwater purification is limited.

settling tank lowered COD by 77%. Filtration reduced COD remaining after prior procedures by 44%.

Traditional sedimentation in a tank is the best way to treat rainwater (Herrmann and Schmida 2000). The filter in the pump pressure pipeline was considered unnecessary and only a 0.5–1.0 mm sieve in the pipe in front of the pump was advised. Due to the formation of carcinogenic and toxic disinfection by-products, chlorination was not used. Another research presents the production of demineralized water from rainwater (Oosterom et al. 2000) with the use of MF, UF, and RO/ion exchange. A benefit of rainwater is its minimal dissolved solids, which greatly decreases scaling and fouling.

In a paper (Shaheed et al. 2017), a 4-chamber was proposed as an inexpensive rainwater purifying system (Fig. 2). Raw water entered the inlet chamber A, then went to the tank with adsorption process with activated carbon (B), and after that in chamber C filtration through sand bed was used. The purified water flowed to chamber (D). The pH of raw rainwater was 6.26–7.31, and after treatment, it increased to 6.53–7.81 (after B) and 6.55–7.55 (after C). Dissolved oxygen concentration in raw water amounted to 8.33–8.79 mg O_2/L and after adsorption of dissolved oxygen by AC, its content in purified water decreased to 7.37–8.32 mg O_2/L. The biochemical oxygen demand (BOD_5) of the collected water was low and reached 1.54–2.58 mg BZT_5/L. After treatment the decrease to 0.82–1.23 mg BZT_5/L of BOD5 content was observed. The concentration of suspended solids did not exceed 10.66 mg/L, and it decreased by about 67–100% after treatment. The *E. coli* ranged from 2 to 14 CFU/ml. The combination of adsorption and filtration through a sand bed enabled 100% elimination of *E. coli* bacteria from the treated rainwater.

A filtration system for highly polluted rainwater was also proposed (Aljerf 2018). Two uniform layers of recycled broken glass and crushed foam glass make up the device, having ecological benefits. This filtration device enhances cleansed water's physical properties

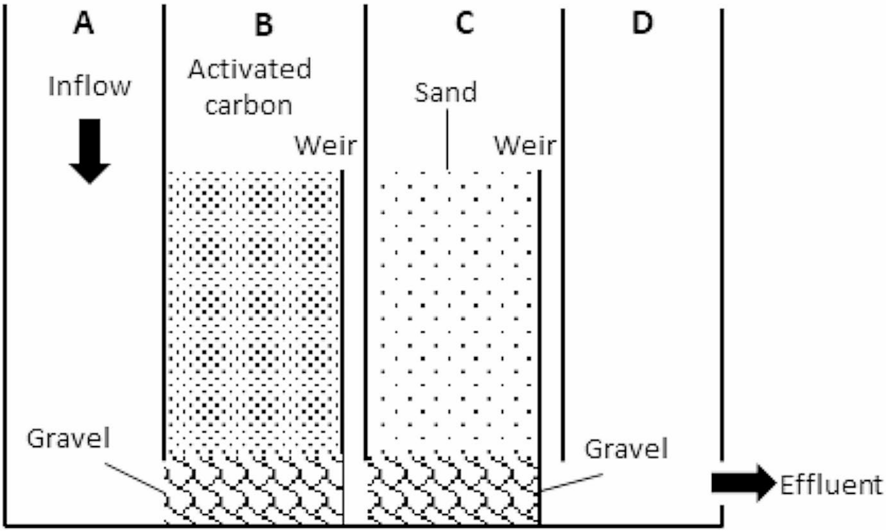

Fig. 2 Rainwater treatment installation scheme (A – influent, B – adsorption chamber, C – filtration, D – clean water tank) (based on (Shaheed et al. 2017)

(reducing color, turbidity, and COD) and enriches it with microelements (K+, Na+, and Mg2 + ions). Copper, lead, and nickel were likewise below detection levels in treated water.

One airport has a rainwater treatment system (Moreira Neto et al. 2012). Water is collected from a 15 × 20 m galvanized roof. Two parallel slow sand filters, a chlorinator, and a 1000-L clean water tank comprise the system.

A rainwater purifying pilot station was tested in work (Pineda et al. 2022). Rainwater was collected for 90 days in the tank, from which was directed to filters. Crushed gravel was the first filter. Ceramic balls accompanied the following filter. Two process versions were tested: (1) After ceramic ball filtration, water went through a quartz sand filter; (2) Natural zeolite was used as the next stage of purification. Treatment ended with UV disinfection. In treated water, dissolved solids did not exceed 1000 mg/L. Quartz sand removed 79% of iron, and zeolite 87%. Zeolite removed up to 82% manganese, and quartz sand up to 73%. After 15 days, iron and manganese removal effectiveness dropped to 68% and 50%, respectively. *E. coli* was 100% eliminated in both cases and increasing operation time reduced microorganism removal.

4 Discussion and Conclusions

RWH systems have grown in popularity and promise water shortage solutions. There are drawbacks and restrictions to implementing this approach. One of the biggest problems is that rainfall is unpredictable and erratic due to seasons. Rainfall can severely affect RWH system performance, e.g. Porto Alegre and Manaus have the most RWH potential in Brazil due to well-distributed and high yearly rainfall (Perius et al. 2021). RWH system performance in the Asian tropical monsoon region is altered by a wide range of additional rainwater (Vuong et al. 2016). Pakistani research (Ali et al. 2021) proved that RWH efficacy depends on local rainfall and system features, e.g. tank size. European research found that tap water savings when replacing it with rainwater vary by geography, rainfall pattern, people's habits, and roof surface. RWH systems in Sant Cugat del Valles, Spain, may save 16% of water for residential usage (Domènech and Saurí 2011). 30–60% savings may be obtained for tanks from 4 to 6 m^3 (Herrmann and Schmida 2000). Recent studies have increasingly examined how climate change affects RWH performance. Studies reveal that greater rainfall may boost water-saving potential but reduce stormwater capture efficiency (Zhang et al. 2019). Climate change in Australia will lower RWH water savings, reliability, and security, especially in the dry season (Haque et al. 2016). According to another study, climate change does not significantly affect RWH, still being a solution to improve water security (Musayev et al. 2018). Research demonstrates the requirement for location-specific and adaptable design of RWH systems with climate change.

Many countries have implemented RWH systems, with Germany being one of the leaders in rainwater collection, next to Japan and Australia. Figure 3 shows European countries where rainwater quality research was conducted and RWH was significantly implemented.

Climate change adaptation in the Netherlands led to political goals for urban water retention. Great Britain has rainwater collection initiatives but no RWH system laws. RWH is underdeveloped in other European nations, but become more popular in Austria, Denmark, and Switzerland. Today, the RWH initiative prioritizes water savings over hydrological, economic, and social benefits. Future studies could examine the RWH system's interaction with urban stormwater infrastructure. A new strategy should address how to market RWH

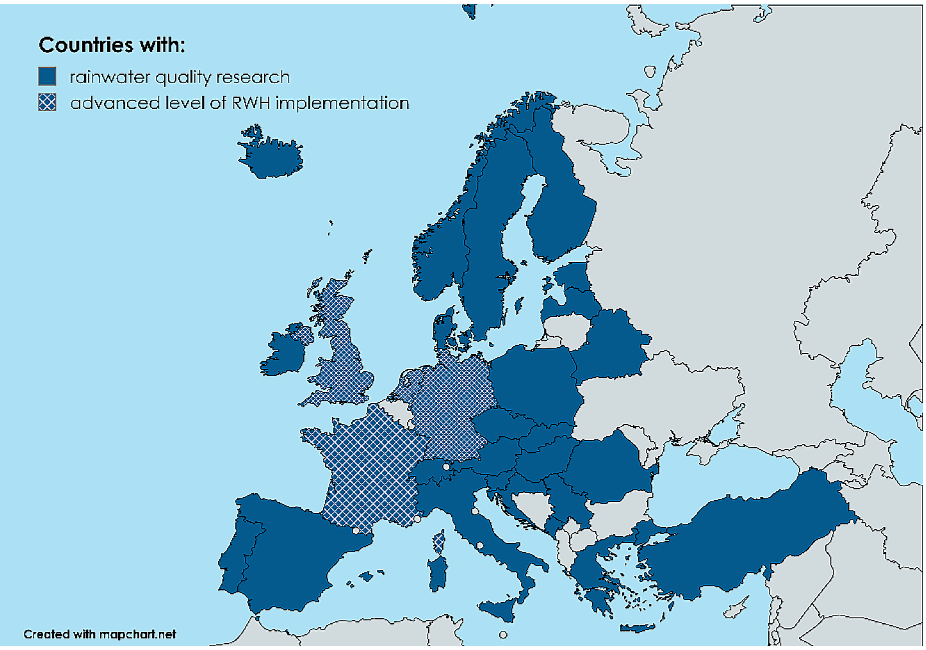

Fig. 3 Map of the study area indicating European countries with research on rainwater quality and a significant degree of RWH implementation

on a broader scale in different nations with diverse climates. Additional effort is needed for pilot-scale installations. Precise technology selection and maintenance are crucial for correct system operation. Today, the payback period is too long for a good return on investment. Large-scale RWH growth requires sustainable institutional and socio-political support to boost incentive tools, awareness, and societal acceptance. 54% of respondents in 12 countries were not concerned about replacing tap water with rainwater. Countries with low water resources are more open to alternative solutions (Stec 2023).

RainWater Harvesting systems should be assessed for energy savings. RWH minimizes tap water use, leading to a decrease in water intake from traditional sources (surface and groundwater) and in the costs of raw water purification. Water supply systems typically consume kilowatt hours to create one cubic meter of water (Scott et al. 2011). Water delivery systems consume 1.71 kWh/m^3 in Germany, 0.68 in Canada, 0.29 in China, and 0.3 in India (Wakeel et al. 2016). Because RWH systems may require a pump, calculating their environmental sustainability and energy savings is complicated (Vieira and Ghisi 2016). Life cycle assessment on specific RWH elements is needed to compare the conventional public water supply and the RWH systems (de Sá Silva et al. 2022). RWH systems reduce energy use and greenhouse gas emissions, mitigating climate change. Estimated reductions in greenhouse gas emissions after the introduction of RWH systems according to research are:

- South Korea – from 0.43 to 0.16 kgCO$_2$-eq/m^3 (Chang et al. 2017);
- Virginia, USA – from 0.85 to 0.41 kgCO$_2$-eq/m^3 (Ghimire et al. 2014);
- Spain – from 1.38 to 0.27 kgCO$_2$-eq/m^3 (Morales-Pinzón et al. 2014).

RWH utilization is still limited by cost. The importance of proper maintenance should also be emphasized. These systems should be checked for possible blockages or leaks, and the condition of tank screens and gutter meshes. An above-ground rainwater tank may be damaged by frost. Draining the tank for winter or isolating it may help. Another problem is algae growth from unrestricted sunlight exposure from inadequate sealing.

To summarize the literature review, it should be emphasized that RWH is a solution that brings both financial and environmental benefits. The progressive climate change led to a necessity of finding alternative water sources, and collecting rainwater is a great solution to meet the water demand and decrease surface runoff of excess rainwater, protecting stormwater drainage systems from overloads and mitigating urban flood risk. RWH systems are not only present in households, nowadays more often appear in public utility facilities, such as office buildings, schools, and even airports, where they can function with great efficiency despite higher water demand. Harvested rainwater can be used for various purposes, but the main drawback is the rainwater quality. Rainwater commonly contains metals, sulfates, nitrate compounds, organic matter, and also microorganisms. Meteorological conditions, air pollution, and collection surface affect its quality. Therefore, the implementation of adequate treatment technologies is necessary. Various purification methods are used, including conventional (surface and underground water purification) and unconventional methods like membrane processes, biological methods, oxidation, and electrocoagulation. For human consumption, rainwater needs to be of the same quality as tap water, which is hard to maintain in households. Therefore, rainwater is used mainly for non-potable uses like washing, cleaning, laundry, watering, and toilet flushing. The future use of rainwater depends on its quality. Based on the above, sufficient rainwater quality legislation is needed to reduce health hazards.

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