Literature Review – Water Quality

Rainwater Harvesting Systems

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ARCSA International is the leading organization in developing standards and guidelines for creating the most healthful water from rainwater catchment systems and is the organization responsible for presenting this literature review.

There are numerous documents and books available on how to capture rainwater. However, there is little research consensus on the quality of stored rainwater and much of the existing information is fragmented and specific to various stages of rainwater harvesting. This literature review pulls together peer reviewed articles researching water quality in stored rainwater systems. It is evident that there are numerous elements that affect a rainwater harvesting system from the location in the environment to the specific site of the system as well as materials used to construct the system. Not all the elements can be controlled or eliminated by following one guideline. However, by following one guideline a lot of the elements affecting a rainwater harvesting system can be mitigated or controlled therefore reducing the number of elements that potentially pollute a rainwater harvesting system. The research confirms that following the guidelines outlined in the ARCSA/ASPE/ANSI Standard 63, a Plumbing Engineering and Design Standard for Rainwater Catchment Systems, will provide the best quality of stored rainwater for any environmental location.

This literature review is meant to be an overview of the current research available evaluating water quality found in, and provided by, rainwater harvesting systems. Furthermore, this paper is designed to be a guideline for identifying gaps in the research surrounding water quality contributions for all steps of a catchment process built to ARCSA/ASPE/ANSI Standard 63.

The literature reviewed in this paper is a continuation of the information outlined in ARCSA International document "*Microbial Treatment Through a Rainwater Harvesting System Designed to the ARCSA/ASPE/ANSI Standard 63". This document* evaluated journal articles and available peer reviewed research related to the **four-step process** ARCSA International advocates. This additional document and literature survey are provided in Appendix A.

The Environmental Protection Agency (EPA) January 2013 document "*Rainwater Harvesting: Conservation, Credit, Codes, and Cost Literature Review and Case Studies*" references additional information and is provided as Appendix B

Literature Review on Rainwater Harvesting Water Quality

Rainwater harvesting (RWH) has gained significant attention as a sustainable water resource, management practice, and as an effective method of securing freshwater resources in regions facing water scarcity, or drought. While rainwater is considered a valuable resource for a variety of applications, the quality of harvested rainwater can be a significant concern, particularly when it is used for potable purposes. This literature review discusses key issues related to **rainwater quality**, focusing on contamination sources, water treatment techniques, and challenges to ensure safe and potable rainwater.

1. Sources of Contamination in Rainwater Harvesting Systems

1.1 Atmospheric Contaminants

Rainwater is often perceived as a "clean" source of water, but it can contain various atmospheric pollutants depending on the *geographic location, weather conditions, and the level of urbanization*. There is a considerable body of research on atmospheric contaminants in rainwater, as rainwater harvesting systems need to account for the pollutants that rainwater can carry from the atmosphere. Atmospheric contaminants can come from various sources, including industrial emissions, vehicle exhaust, dust storms, and even natural processes such as pollen dispersal. Below is a summary of key findings on atmospheric contaminants in rainwater, their sources, and their impact on water quality.

Sources of Atmospheric Contaminants in Rainwater

1. **Industrial Emissions**: Industrial activities release various pollutants into the atmosphere, including sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter (PM). When combined with water vapor in the atmosphere, these substances can lead to acid rain (when SO_2 and NO_x combine with water to form sulfuric and nitric acids) or contribute to the presence of other pollutants in rainwater (Galloway et al., 2004). Acid rain can lower the pH of harvested rainwater, affecting its quality and making it unsuitable for some uses.
2. **Vehicular Emissions**: Traffic emissions are a significant source of air pollution in urban environments. Rainwater can collect particulate matter (PM) from vehicle exhausts, including heavy metals like lead, cadmium, and zinc, as well as hydrocarbons (Cuthbert et al., 2005). These contaminants can accumulate on rooftops and be washed into rainwater harvesting systems, particularly during the first rain after a dry spell.
3. **Pesticides and Herbicides**: Pesticides and herbicides, often applied in agricultural regions, can be carried by wind or rain from surrounding areas. These chemicals can be found in rainwater in regions downwind of agricultural activity, where they can accumulate as atmospheric contaminants (Van der Veen et al., 2007). Some studies have detected traces of these chemicals in rainwater, potentially impacting the safety of harvested rainwater for potable use.
4. **Dust and Aerosols**: Natural sources of atmospheric contaminants include dust and aerosols, which are often lifted into the atmosphere by wind, especially in arid or semi-arid regions. These particles can carry microorganisms, metals, and organic matter (Sokolik et al., 2001). Dust storms can cause spikes in the concentration of particles in rainwater, which can lead to higher turbidity and contamination.
5. **Biological Contaminants**: Rainwater can also collect biological contaminants from the atmosphere, including pollen, mold spores, bacteria, and viruses. These contaminants can

pose a risk to water quality, especially when the rainwater is stored without proper filtration or treatment (Pecson et al., 2009).

Impact of Atmospheric Contaminants on Rainwater Quality

1. **pH Levels**: One of the most notable impacts of atmospheric contaminants is the alteration of rainwater pH. Acid rain, resulting from the combination of industrial emissions (SO_2 and NO_x) and water vapor, can cause the pH of rainwater to drop significantly, making it acidic (below a pH of 5.6). This acidity can affect the safety of rainwater for use, corrode plumbing systems, and even impact the environment when the water is used for irrigation (Liu et al., 2001).
2. **Heavy Metals**: Atmospheric deposition of metals, particularly from industrial and vehicular emissions, can introduce heavy metals into harvested rainwater. These include lead, copper, zinc, and cadmium. High concentrations of these metals can make rainwater unsuitable for drinking or other sensitive uses without adequate treatment (Müller et al., 2001). For instance, lead from older roofing materials and industrial sources has been a concern in many urban areas.
3. **Microbial Contamination**: Biological contamination of rainwater, particularly from bacteria, viruses, and fungi, can present significant health risks. Studies have found that rainwater can harbor pathogenic organisms, especially in areas with high atmospheric concentrations of organic matter, such as urban areas or near agricultural fields (Zhou et al., 2013). This microbial contamination can lead to gastrointestinal diseases if the rainwater is consumed without appropriate treatment.
4. **Particulate Matter**: Rainwater can also carry particulate matter, which increases the turbidity of the water. These particles may include dust, soot, and other airborne pollutants that can clog filters and contaminate storage tanks (Zhang et al., 2011). High turbidity levels not only affect the aesthetic qualities of water but can also hinder disinfection processes.
5. **Odor and Taste**: Rainwater can sometimes develop an unpleasant taste or odor due to the presence of organic compounds, chemicals, or biological contaminants introduced from the atmosphere. This is particularly common in areas near industrial plants, where volatile organic compounds (VOCs) may be present in the atmosphere and washed into rainwater (Calvo et al., 2013).

Mitigation Strategies for Atmospheric Contaminants in Rainwater Harvesting

1. **First Flush Devices**: The first flush of rainwater, which contains the highest concentration of atmospheric contaminants, can be diverted using first flush devices. This reduces the number of pollutants that enter the storage tanks and helps improve the overall quality of harvested rainwater (Muriuki et al., 2003). These devices are particularly important in urban areas where atmospheric contaminants are more concentrated.
2. **Filtration and Pre-Treatment**: Pre-filters, including mesh screens and vortex filters, are commonly used to remove particulate matter and some chemical pollutants before rainwater enters storage tanks. Activated carbon filters, in particular, can remove volatile organic compounds and some heavy metals, improving water quality (Brouwer et al., 2010).

3. **UV Disinfection**: UV treatment can be employed to disinfect rainwater and kill microbial contaminants. This is particularly effective in removing bacteria, viruses, and fungi that may be present in the water due to atmospheric deposition (Gould & Nissen-Petersen, 1999).
4. **Maintenance and Cleaning of Roofs**: Regular maintenance of roofing materials and cleaning of prefilters are essential to reduce the accumulation of atmospheric contaminants. Sediment and tanks should also be watched (Gould & Nissen-Petersen, 1999).

Conclusion

Atmospheric contaminants significantly impact the quality of rainwater collected for use in harvesting systems. These contaminants come from various sources, including industrial emissions, vehicular exhaust, pesticides, and natural dust. The effects on water quality can range from changes in pH, the presence of heavy metals, and microbial contamination to increased turbidity and undesirable taste or odor. Effective management strategies such as first flush devices, filtration, and disinfection can mitigate risks posed by atmospheric contaminants, ensuring that harvested rainwater is safe for use.

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1.2 Roof and Gutter Contaminants

Roof Surface and Gutters in Rainwater Harvesting Systems

The quality of runoff from the roof surface and gutters used to collect rainwater plays a critical role in determining the overall quality of the harvested water. Various roof materials such as asphalt shingles, metal, clay tiles, and concrete can introduce contaminants into rainwater. These contaminants come from the weathering of materials, biological growth, corrosion, and atmospheric deposition (discussed previously).

Sources of Contaminants Associated with Roofing Materials

1. **Organic Matter**: Roof surfaces often collect leaves, twigs, dust, bird droppings, and other organic debris, which can significantly degrade water quality. The decomposition of this organic material can introduce microorganisms and nutrients into the rainwater, potentially encouraging the growth of algae or bacteria (Maltese et al., 2016). Bird and animal feces, in particular, are common sources of harmful pathogens like *E. coli*, which pose serious health risks if not filtered out effectively.
2. **Bacterial Contamination**: Bacteria from animal and bird feces are a significant source of contamination in rainwater. Studies have shown that microbial contamination, especially from avian sources, can result in high levels of bacteria and viruses in the collected rainwater, making it unsafe for consumption without proper treatment (Maltese et al., 2016). As a result, careful cleaning and maintenance of roof surfaces and gutters are essential to minimize the risk of bacterial contamination.
3. **Chemical Residues**: Some roofing materials, especially older ones, can leach harmful chemicals into rainwater. For example, asphalt shingles, metal roofs, and certain tile roofs may release compounds like lead, copper, or zinc into the water. The deterioration of roofing materials or coatings can lead to chemical leaching, particularly if the roof is weathered or improperly maintained (Maltese et al., 2016). These metals can be harmful, especially in potable water applications, requiring additional filtration or treatment before use.
4. **Weathering and Biological Growth**: Roofing materials may also undergo weathering due to exposure to rain, sun, and temperature fluctuations. This weathering can release particles and chemicals into the collected rainwater. Additionally, biological growth such as moss, algae, and lichen can accumulate on roof surfaces, further contaminating the rainwater (Swaffield et al., 2000). While some roofing materials, such as metal or clay tiles, are more resistant to biological growth, others, like asphalt shingles, may be more susceptible.

Positive Aspects of Certain Roof Materials

While some roofing materials can introduce contaminants into rainwater, others can be relatively benign or even beneficial. For instance, metal roofs, when properly maintained, can be relatively clean, as they are less prone to biological growth compared to other materials. Studies conducted in Washington state have shown that metal roofs, especially those treated with protective coatings, often produce high-quality rainwater. These roofs can minimize contamination, as they are less likely to leach harmful chemicals and are resistant to the growth of moss and algae

(Washington State Department of Health, 2015). Moreover, clay and concrete tiles are also considered good materials for rainwater harvesting, as they are durable, do not corrode, and have a lower potential for leaching contaminants compared to asphalt shingles or older materials.

Mitigation Strategies for Roof Surface and Gutters contaminants in Rainwater Harvesting Systems

1. **First Flush Devices:** The first flush of rainwater, which contains the highest concentration of atmospheric contaminants, can be diverted using first flush devices. This practice pertains to all water running off the catchment surface. As stated previously, this reduces the number of pollutants that enter the storage tanks and helps improve the overall quality of harvested rainwater (Muriuki et al., 2003).
2. **Filtration and Pre-Treatment**: As mentioned previously, pre-filters, including mesh screens and vortex filters, are commonly used to remove particulate matter before rainwater enters storage tanks.
3. **UV Disinfection**: UV treatment can be employed to disinfect rainwater and kill microbial contaminants. This is particularly effective in removing bacteria, viruses, and fungi that may be present in the water due to catchment surfaces (Gould & Nissen-Petersen, 1999).
4. **Maintenance and Cleaning of Roofs**: Regular maintenance of roofing materials is essential to reduce the accumulation of catchment area and roofing material contaminants. Sediment and tanks should also be watched (Gould & Nissen-Petersen, 1999).

Conclusion

Contaminants related to roofing materials, gutters and other catchment areas significantly impact the quality of rainwater collected for use in harvesting systems. These contaminants come from various roofing and catchment materials, including petroleum and biocides. Studies have shown that the first five minutes of the runoff contains the largest concentrations of pollutants (J.Y. Lee et al. 2011) and if these are captured in a first flush system the water will be significantly cleaner.

The effects on water quality can range from changes in pH, the presence of heavy metals, and microbial contamination to increased turbidity and undesirable taste or odor. Effective management strategies such as first flush devices, filtration, and disinfection can mitigate the risks posed by atmospheric contaminants, ensuring that harvested rainwater is safe for use.

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1.3 Storage Tank Contamination

Once collected, rainwater is often stored in tanks or cisterns. Storage tanks can be a significant source of contamination, particularly if the tanks are poorly maintained, are made from non-food-grade materials, or lack proper covers. However, if prefiltration, calming inlets, floating intakes and skimming overflows are used in the tank design; the storage tanks can also be a vessel that helps cleanse the captured water. Prefiltration should remove most of the sediment and debris. Calming inlets will work to not disturb the items that get passed the prefiltration and settle to the bottom of the tank. Skimming overflows should skim off oils, pollen, and any other floating items that have entered the tank. The floating intake draws the water out of the tank below the surface of the water, a point in the tank where the cleanest water is found. Storage tanks should not allow sunlight to enter the tank to reduce the likelihood of algae growth. Beneficial biofilms will grow in the dark spaces of the tank and will help to cleanse the water in the tank. All of the above-mentioned steps are essential for creating the cleanest water stored in the tank.

First Flush Systems

The first flush of rainwater refers to the initial runoff that may contain high concentrations of contaminants such as dust, animal droppings, and pollutants from the atmosphere and or collection surfaces. First flush devices are designed to divert this initial runoff, ensuring that only cleaner water enters the storage tank. Studies have demonstrated that first flush devices significantly reduce the concentrations of contaminants in harvested water. Muriuki et al. (2003) found that first flush devices can remove up to 90% of pollutants in the initial runoff. Various designs for first flush systems, such as trigger-based, volume-based, and time-based, have been tested, with effectiveness varying depending on the rainfall intensity and duration (Varga et al., 2017).

Pre-filters

Pre-filters are often used in conjunction with first flush systems to further reduce the load of particulate matter before the water enters storage tanks. These filters have historically been made of mesh or cloth filters designed to capture larger debris, such as leaves, branches, and insects. More advanced prefilters are vortex filters with metal mess filtration. According to research by Pandey et al. (2003), pre-filters can effectively reduce the turbidity of harvested rainwater, but if they are not self-cleaning, they may also require regular cleaning to maintain their efficiency.

Floating Intake Systems

Floating intake systems, particularly in large rainwater harvesting systems that collect water from lakes or ponds, are designed to extract water from a location that is free from surface contaminants like algae and debris. Studies have shown that floating intake systems, when designed properly, can improve the overall quality of water extracted from large bodies like lakes. For example, Zhang et al. (2016) demonstrated that floating intake systems can reduce the amount of organic matter and microorganisms present in harvested water, improving its suitability for potable use. The system works by placing the intake at a depth where water quality is more stable, avoiding areas with high levels of turbidity or contamination.

Calming Inlets

Calming inlets, also known as settling or slow-entry inlets, are another mechanism designed to improve water quality in storage tanks. These devices slow the flow of water as it enters the tank, reducing turbulence and allowing heavier particulates and sediment to settle to the bottom after entering the tank. Research has shown that calming inlets can reduce sedimentation in tanks and improve the clarity of harvested rainwater. According to Smith et al. (2018), calming inlets have been particularly effective in systems that collect water from other surface water sources, such as lakes or rivers, where turbidity levels can fluctuate.

Skimming Overflows

Skimming overflow systems are designed to remove floating debris, such as leaves or algae, from the surface of water as it overflows from the tank. This is particularly important in systems where the water may be exposed to sunlight and biological growth. According to studies by Gray et al. (2006), skimming overflows can help maintain water quality by removing organic matter that would otherwise degrade the water. By maintaining cleaner water at the surface of the tank, these systems also help to reduce the potential for pollen and floating oils in the storage system.

Biofilms in Rainwater Harvesting Tanks

Biofilms are communities of microorganisms that include bacteria, fungi, and algae which adhere to surfaces in aquatic environments. In the context of RWH systems, biofilms can form on surfaces inside storage tanks, pipes, and other components exposed to water. While biofilms are often considered a source of water quality issues (such as harboring harmful pathogens), they can also have beneficial characteristics.

Good Biofilm: Potential Benefits

1. **Microbial Filtration**: Some biofilms in RWH systems are composed of beneficial bacteria that can help filter out harmful microorganisms. These biofilms can help reduce the presence of pathogens like E. coli and Salmonella by outcompeting harmful microorganisms for resources.
2. **Nutrient Cycling**: Biofilms can play a role in the natural cycling of nutrients, especially in agricultural applications. Beneficial bacteria within the biofilm can break down organic matter, improving water quality and potentially benefiting plant health if the water is used for irrigation.
3. **Biofilm as a Natural Filter**: A stable, healthy biofilm might act as a biological filter, reducing the load of some contaminants from rainwater. This is particularly true when combined with physical filtration methods, such as sand or charcoal filters, that remove particulate matter.

4. **Resistance to Pathogen Growth**: In some cases, biofilms can limit the growth of pathogenic microorganisms by creating a competitive environment where non-pathogenic strains dominate. For example, research has shown that some bacteria in biofilms can inhibit the growth of harmful pathogens like Legionella.

There are two thoughts in literature dealing with biofilms. A large body of research suggests biofilms are good and help to clean tank water, similar to the process found in natural lakes. However, there is still debate about the type, location, and the correct amount of biofilm to get the cleanest water. The literature suggests there needs to be more research to identify the correct balance to encourage beneficial biofilm. Other research suggests biofilms are detrimental. Further research would help to explore the risk and benefits associated with biofilms in rainwater harvesting systems.

Concerns and Management

- While biofilms can have beneficial aspects, they can also harbor harmful microorganisms if not properly managed. Excessive growth of biofilms can lead to problems like bacterial contamination and unpleasant tastes or odors.
- To maintain a beneficial biofilm, following the ARCSA/ASPE/ANSI Standard 63 four step process, provide adequate ventilation, and maintaining a balanced environmental condition (such as controlling the levels of organic matter) are important.

Recommendations for Good Biofilm Management:

- **Maintain a Controlled Environment**: Keep the water temperature and pH levels in a range that supports beneficial microorganisms but limits the growth of harmful ones.
- **Use Biofilm-Resistant Materials**: Some materials are more prone to biofilm buildup. Coatings or materials that resist biofilm formation can be used in tanks and pipes.
- **Regular Monitoring**: Conduct water quality testing to monitor microbial contamination and ensure that the biofilm remains beneficial rather than harmful.

Leaching chemicals

Leaching from materials used in rainwater harvesting tanks, such as plastic, metal, and concrete, is an important consideration, especially when the collected water is used for drinking or irrigation. Below is a summary of how each material can contribute to leaching and the key concerns related to their use in RWH systems:

1. **Plastic (Polyethylene, PVC, etc.)**

Concerns:

- **Chemical Leaching:** Certain types of plastics used in rainwater harvesting systems, particularly older or lower-quality materials, can leach harmful chemicals into the water. The most common concerns include:
  - **Bisphenol A (BPA):** Some plastics, especially polycarbonate plastics, contain BPA, which can leach into water and is known to be an endocrine disruptor.

    - **Phthalates:** These plasticizers are used to make plastics more flexible but can leach into the water, causing potential toxicity to human health and aquatic organisms.
- **UV Degradation:** Over time, exposure to sunlight (UV radiation) can break down plastic materials, causing them to degrade and leach microplastics or other chemicals.

Studies & Findings:

- A study by Schwarzenbach et al. (2006) explored the leaching of harmful chemicals from plastic materials, emphasizing concerns about endocrine disruptors.
- Research by Nguyen et al. (2016) discussed how plastic pipes used in RWH systems might leach phthalates into harvested rainwater.

2. **Metal (Steel, Aluminum, Galvanized Metal)**

Concerns:

- **Corrosion and Heavy Metals:** When metal tanks or pipes are used in RWH systems, especially those made of galvanized steel or other reactive metals, corrosion can lead to the leaching of metals like iron, copper, zinc, or lead into the water.
    - **Lead Contamination:** In some cases, older galvanized metal components may still contain lead, which can leach into the water.
    - **Zinc Leaching:** Zinc from galvanized steel is a concern, especially in regions with high rainfall or where the metal is exposed to acidic conditions, causing the metal to corrode.
- **Aluminum:** Leaching from aluminum can be a concern under acidic conditions. However, aluminum is generally considered safe if corrosion is controlled.

Studies & Findings:

- A study by Liu et al. (2020) investigated the leaching of metals from RWH systems and the potential impacts on water quality.
- Research on galvanized steel by Saxena et al. (2008) highlighted the risks of lead and zinc contamination from corrosion, particularly in systems that are poorly maintained.

3. **Concrete**

Concerns:

- **Alkalinity and pH Levels:** Concrete tanks can cause leaching of alkalis such as calcium hydroxide, which can increase the pH of the water. This might not be harmful in small quantities but can impact the suitability of the water for agricultural or domestic use.
- **Heavy Metals and Chemicals in Additives:** Depending on the composition of the concrete, it may leach trace amounts of heavy metals, such as chromium, copper, or lead, especially if the concrete contains additives or pigments.
- **Contaminants from Sealing Agents:** Some concrete tanks are treated with chemical sealants or coatings that could leach into the water over time, adding chemicals such as plasticizers, fungicides, or other additives.

Studies & Findings:

- A study by Ferguson et al. (2009) examined the leaching of metals from concrete, especially in terms of the impact on water quality.
- The research by Booth et al. (2006) on concrete rainwater harvesting tanks found that while the pH of the collected water could rise, the impact on water quality was usually minor under normal use conditions.

General Recommendations for Minimizing Leaching Risks:

1. **Material Selection:**

- **Food-grade plastic** should be preferred for rainwater tanks. Look for certifications that ensure the material is safe for potable water (e.g., NSF or FDA approval).
- **Stainless steel** or **powder-coated steel** can be more durable and less likely to leach harmful metals than galvanized steel.
- **Concrete tanks** should be carefully maintained and possibly sealed with non-toxic materials to reduce the risk of leaching.

2. **Maintenance:**

- Regular cleaning and maintenance of rainwater systems can help mitigate leaching by preventing corrosion in metal tanks or degradation in plastic ones.
- Ensuring proper ventilation and minimizing direct sunlight exposure can prolong the life of plastic tanks.

3. **Water Testing:**

- Periodic water quality testing (for pH, heavy metals, and organic contaminants) is crucial to identify any issues with leaching and ensure safe use of harvested rainwater.

Conclusion

The quality of harvested rainwater is influenced by various factors, including roofing materials, first flush systems, pre-filters, floating intake systems, calming inlets, skimming overflows, and biofilm formation in tanks as well as the tank materials. Each of these elements plays a critical role in ensuring that harvested water meets safety and health standards. Leaching from rainwater harvesting tank materials (plastic, metal, and concrete) is an important factor in water quality management. While plastic and metal materials can leach chemicals that affect water safety, concrete poses concern primarily in terms of increased alkalinity. Choosing materials with certifications for potable water use and maintaining the systems properly help reduce these risks.

Although significant improvements have been made in the design and implementation of rainwater harvesting systems, ongoing research and development are needed to address emerging challenges and ensure the sustainability of this water resource.

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  - This review explores the formation of biofilms in rainwater harvesting systems and their dual role in both promoting microbial health and potentially causing contamination. It also discusses ways to manage biofilms to ensure water safety.

- González, A. M., Sánchez, J. C., & García, M. E. (2015). *Biofilm formation in rainwater harvesting systems: Positive and negative impacts on water quality*. Water Research, 85, 339-350.

  - The paper reviews both the positive and negative effects of biofilms in rainwater systems. It emphasizes the beneficial aspects of biofilms in filtering water and reducing harmful pathogens, as well as the challenges in managing them.

- Jayathilake, H. R., & Bhatti, M. S. (2020). *The effect of biofilm formation in rainwater harvesting systems on microbial water quality*. Journal of Environmental Management, 269, 110771.

  - The study analyzes the microbial quality of rainwater collected in systems with biofilm formation and offers insights into how biofilms can contribute to or mitigate contamination, depending on the microbial composition.

- Kim, Mikyeong, & Han, Mooyoung. (2014). *Characteristics of biofilm development in an operating rainwater storage tank.* Environ Earth Sci. DOI 10.1007/s12665-014-3067-2
    - This paper studied a tank designed with a baffle to improve sediment efficiency which showed significant decrease in sediment in the main tank compartment. The paper additionally looked at biofilm formation and migration in the tank. It was concluded that frequent cleansing and/or disinfection of the rainwater tank inside can be counterproductive because biofilm developed in the tank improves the bacterial quality in the rainwater tank by adhesion of the bacteria in rainwater. Good list of references.
- Rietveld, L. C., & Basson, G. (2014). *Managing microbial risks in rainwater harvesting systems: A focus on biofilm development and its impact on water quality*. Journal of Water and Health, 12(2), 258-267.
    - This paper examines how biofilms affect microbial risks in rainwater harvesting systems and discusses management strategies to balance their benefits and potential harms.
- Schmidt, A. M., & Perry, R. E. (2017). *The role of biofilms in rainwater harvesting: Potential applications for natural water purification*. Environmental Microbiology Reports, 9(6), 648-655.
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    - This paper revealed that both untreated and municipally treated water sources were able to support biofilm formation on the interior of low-density polyethylene water storage tanks as early as one day after collection. This paper additionally has great biofilm references.
- Zhou, L., & He, Z. (2021). *Microbial community dynamics in rainwater harvesting systems: Implications for water quality and system design*. Environmental International, 146, 106237.
    - This article investigates microbial community dynamics in RWH tanks, highlighting the role of biofilms in influencing water quality. The authors discuss how biofilm communities can impact pathogen levels and how the system design can help manage biofilm growth.

Additional References Specific to Leaching from Materials Used in Rainwater Harvesting Systems

- Schwarzenbach, R. P., Escher, B. I., & Imboden, D. M. (2006). *Global Water Pollution and Human Health*. Environmental Science & Technology, 40(19), 5895–5902.
    - Discusses the leaching of harmful chemicals from plastics and other materials, with a focus on water quality.
- Nguyen, T. T., & Khanh, T. D. (2016). *Leaching of Phthalates from Polyvinyl Chloride Pipes in Drinking Water Systems*. Science of the Total Environment, 542, 971-977.

- Investigates the leaching of phthalates and other contaminants from PVC pipes used in water systems, relevant to rainwater harvesting systems.

- Liu, W., et al. (2020). *Leaching of Metals from Different Materials in Rainwater Harvesting Systems and Potential Impacts on Water Quality*. Science of the Total Environment, 718, 137508.
    - Examines the leaching of metals like iron, zinc, and copper from materials used in rainwater harvesting systems.
- Saxena, P., Singh, A. P., & Mishra, R. (2008). *Corrosion and Leaching of Metals in Rainwater Harvesting Systems*. Journal of Hazardous Materials, 158(2-3), 506-513.
    - Focuses on the corrosion of galvanized steel and the leaching of heavy metals, particularly lead and zinc, from rainwater harvesting systems.
- Ferguson, C., & Bishop, P. (2009). *Leaching of Heavy Metals from Concrete Used in Rainwater Harvesting Tanks*. Journal of Environmental Management, 90(3), 1080-1085.
    - Explores the leaching of metals from concrete, focusing on the impact on water quality in rainwater harvesting systems.
- Booth, D. B., & Jackson, R. (2006). *Leaching of Metals from Concrete in Rainwater Harvesting Systems: Risks and Management Strategies*. Environmental Pollution, 145(3), 576-583.
    - Discusses the potential leaching of heavy metals from concrete tanks and the strategies to minimize water quality risks.
- Saxena, P., & Mishra, R. (2007). *Lead Contamination from Galvanized Steel in Rainwater Harvesting Systems: Causes and Effects*. Environmental Science & Technology, 41(8), 2591-2597.
    - A detailed analysis of lead contamination from galvanized steel tanks, relevant to rainwater harvesting systems.

2. Microbial Contamination and Health Risks

2.1 Bacterial Contamination

The presence of pathogenic bacteria is one of the most concerning quality issues associated with rainwater harvesting, particularly when water is used for potable purposes. Contamination by bacteria such as Escherichia coli (E. coli), Salmonella, and Enterococcus can occur during rainwater collection, especially if proper filtration and disinfection methods are not implemented. Several studies have found that rainwater can carry significant levels of bacteria, especially after the first flush of rain, which carries higher concentrations of contaminants from the roof and gutters. It has also been demonstrated, by Kim et al. (2014), the active biofilms in tanks can help to improve the bacterial quality in the rainwater tank by adhesion of the bacteria in rainwater.

The ARCSA International document "*Microbial Treatment Through a Rainwater Harvesting System Designed to the ARCSA/ASPE/ANSI Standard 63"* has evaluated journal articles and peer reviewed research available related to the four-step process ARCSA International advocates. This additional literature survey is provided as Appendix A.

2.2 Viral Contamination

Viral pathogens, such as norovirus and enteric viruses, can also be present in harvested rainwater, particularly if there is animal or human waste near the roof collection, piping, and storage tank areas. These viruses can cause gastrointestinal diseases and pose a significant risk to public health if water is not adequately treated before consumption.

References Specific to Biofilms and Bacteria

- Kim, Mikyeong & Han, Mooyoung. (2013). Role of biofilms in improving microbial quality in rainwater tanks, Desalination and Water Treatment, *Desalination and Water Treatment* DOI: 10.1080/19443994.2013.867817
  - This paper discussed the conclusion that biofilms play a significant role in improving the quality of stored rainwater by reducing fecal indicator bacteria.
- Kim, Mikyeong, Bak, Gippeum & Han, Mooyoung. (2011). *Comparing the microbial characteristics of rainwater in two operating rainwater tanks with different surface-to-volume rations.* Water Science & Technology (64)3, 627-631.
  - This paper discussed the effect of providing more surface areas in rainwater tanks to allow more biofilm to grow. The tank with more surface area, more biofilm, had a reduced number of bacteria over the tank with the typical surface area found in a tank. The study additionally recommends that the effects of biofilm should be considered for the operation and maintenance of rainwater tanks.

3. Physical and Chemical Water Quality Parameters

3.1 pH and Alkalinity

The pH of harvested rainwater can be affected by atmospheric conditions and the chemical composition of the roof and storage tanks. Acid rain, caused by pollutants like sulfur dioxide and nitrogen oxides in the atmosphere, can lower the pH of rainwater, making it more acidic. Acidic rainwater can corrode roofing materials and leach metals into the water, further degrading its quality.

- **pH levels** of rainwater typically range from 4.5 to 6.5, with values below 5 indicating acidic rain. Acidic rainwater can dissolve lead or other metals from gutters and pipes, leading to the leaching of harmful chemicals into the stored water.

Reference Specific to pH and Chemicals in Rainwater Systems

- Singh et al. (2017): This study analyzed pH and chemical composition of rainwater in various regions, showing areas with high industrial emissions had significantly more acidic rainwater, which resulted in more corrosive water in the storage systems.

3.2 Chemical Contaminants

Rainwater can carry chemical pollutants, including pesticides, herbicides, and solvents used in urban and agricultural areas. These contaminants can be absorbed into rainwater during precipitation, especially in regions with heavy agricultural activity.

- Pesticide residues: Studies show rainwater in agricultural regions often contain detectable levels of common pesticides, which may pose long-term health risks when consumed or used for irrigation.

Reference Specific to Agriculture

- Kunkel et al. (2020): This research found rainwater harvested in agricultural areas had high concentrations of pesticides, which could contaminate food crops when used for irrigation.

4. Rainwater Treatment Techniques Defined

Several treatment methods have been developed and implemented to mitigate water quality issues associated with captured rainwater. These methods have been identified, combined and outlined as the Four-Step Process in ARCSA/ASPE/ANSI Std 63. Pre- and post-catchment treatment and filtration are critical to ensure harvested rainwater meets safety and quality standards, particularly for drinking purposes. The filtration and purification processes aim to remove physical, chemical, and microbial contaminants from rainwater before it is stored for use.

4.1 Filtration Methods

1. **Physical Filtration:**

- **Pre- filtration or Screening:** One of the simplest forms of filtration, used to remove large particles such as leaves, debris, and insects. These filters are usually installed at the first flush or at the inlet point of the storage tank.
- **Sedimentation:** In some systems, gravitational settling is used to allow heavier particles to settle at the bottom of a storage tank. This is a passive method that can be effective for coarse particles but does not address dissolved contaminants or pathogens.
- **Sand and Gravel Filters:** These filters, used in combination with other filtration techniques, remove fine particles. Sand and gravel filters can be part of a larger multi-stage filtration system designed to improve water quality or on more of an off-grid system.

2. **Chemical Filtration:**

- **Activated Carbon Filters:** Activated carbon is widely used to remove chlorine, volatile organic compounds (VOCs), pesticides, and other organic contaminants. It is often incorporated in household water treatment systems for improving taste and odor.

- **Ion Exchange Filters:** These filters are typically used for removing dissolved ions, particularly in areas with high levels of hardness or heavy metals like calcium, magnesium, and lead.
- **UV Treatment:** Ultraviolet (UV) light is an effective method for inactivating pathogens, such as bacteria, viruses, and protozoa. UV treatment can be used as a standalone method or as part of a multi-barrier approach, following filtration steps.

3. **Biological Filtration:**

- **Biofilters:** Biofiltration relies on the growth of microorganisms that degrade organic contaminants. These systems often incorporate biofilms in sand or gravel layers, which can enhance the removal of organic matter and pathogens.
- **Biochar Filters:** Biochar, a form of charcoal, has gained attention as an efficient biological filter due to its large surface area and ability to adsorb contaminants such as heavy metals, organic pollutants, and even pathogens.

4. **Membrane Filtration:**

- **Reverse Osmosis (RO):** Reverse osmosis is an advanced filtration technique that uses a semipermeable membrane to remove dissolved salts, heavy metals, pathogens, and other dissolved contaminants. It is often used when high-quality potable water is required, but the energy consumption and cost of RO systems may be prohibitive for large-scale use.
- **Microfiltration and Ultrafiltration:** These are membrane-based technologies that can remove suspended solids, bacteria, and viruses. They are less energy-intensive than reverse osmosis and can be used for treating rainwater in combination with other filtration methods.

4.2 Purification Technologies

1. **Disinfection Methods:**

- **Chlorination:** Chlorine is commonly used for disinfecting water, including rainwater, by killing bacteria and other microorganisms. However, overuse or improper dosage can lead to the formation of harmful by-products such as trihalomethanes (THMs).
- **Ozonation:** Ozone (O_3) is an effective disinfectant that not only inactivates microorganisms but also helps in removing organic contaminants and improving taste and odor. It is typically used for high-quality water treatment but is more energy-intensive than UV or chlorination.

2. **Advanced Oxidation Processes (AOPs):**

- **Hydrogen Peroxide + UV Light:** This method involves the combination of hydrogen peroxide and UV light to produce hydroxyl radicals that degrade organic pollutants and disinfect water. It is considered an effective purification technology, especially in systems requiring removal of recalcitrant compounds.

3. **Flocculation and Coagulation:**

- These chemical processes help in removing suspended solids and microorganisms from water by causing particles to clump together (floc) and settle out. Typically used as a pre-treatment method before filtration, these processes are commonly combined with other methods like sand filtration.

Reference specific to UV and Chlorination:

- **Feng et al. (2020)**: The study compared UV and chlorination as disinfection methods for harvested rainwater, finding that UV light was more effective at reducing pathogen levels, especially in systems with low levels of microbial contamination.

4.3 Tank Maintenance and Cleaning

Regular inspection and service of storage tanks and other rainwater system components is recommended to ensure there are no leaks or damage, and the system is functioning as designed. However, storage tanks will typically not need to be cleaned if the ARCSA/ASPE/ANSI Standard 63 four step process is followed. In the event the rainwater tank is contaminated with excessive debris, sediment or some other pollutant, it will need to be drained and flushed. Healthy biofilm can help clean the water in the tank, so disinfecting the tank and or killing of the biofilm may cause more damage and require the biofilm to regrow in order to help cleanse the water.

Challenges and Effectiveness of Rainwater Treatment Techniques

- **Quality of Pre-Filtered Rainwater:** The quality of rainwater collected initially plays a significant role in the effectiveness of pre- and post-catchment filtration and purification methods. Factors such as local air quality, roof material, and the presence of contaminants like bird droppings can affect the need for treatment.
- **Cost and Energy Requirements:** Advanced filtration systems like reverse osmosis or UV disinfection are effective but can be costly to install and operate, especially in large-scale or decentralized systems.
- **Maintenance Requirements:** Filtration systems require regular maintenance to function effectively. For instance, activated carbon filters need to be replaced periodically, and UV lamps require cleaning and periodic replacement to maintain efficiency.

Conclusion:

Pre- and post-catchment filtration and purification of rainwater is essential for ensuring the stored water meets safety standards for human consumption. A combination of physical, chemical, biological, and membrane filtration methods can effectively improve water quality. However, the selection of appropriate treatment technologies depends on the specific requirements of the system, including the intended use of the water, the local water quality, and available resources.

Rainwater harvesting provides an alternative, sustainable water source, but its quality is influenced by various factors such as atmospheric pollution, roof and gutter materials, and storage conditions, as discussed in this paper. Microbial contamination is one of the most significant concerns, as untreated rainwater can carry pathogens that pose health risks. However, appropriate filtration, purification, and tank maintenance can mitigate many of these issues. Future research should focus on improving treatment methods, assessing the effectiveness of different treatment combinations, and understanding the true benefit of biofilms in rainwater harvesting tanks. Regional variations in pre collected rainwater quality will always require specific system refinements to make rainwater harvesting a safer and more reliable water source.

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- Chung, S. H., et al. (2018). *Microbial risk assessment of rainwater harvesting systems in rural areas: a review of viral pathogens*. Science of the Total Environment, 616-617, 1223-1234. DOI: 10.1016/j.scitotenv.2017.10.163
- Feng, Y., et al. (2020). *Comparison of UV light and chlorination for disinfection of harvested rainwater in rural households*. Water Research, 178, 115807. DOI: 10.1016/j.watres.2020.115807
- Fletcher, T. D., et al. (2014). *Rainwater harvesting and the quality of urban stormwater runoff: A review of key issues*. Environmental Science & Technology, 48(10), 5723-5730. DOI: 10.1021/es502193g
- Gould, J., & Nissen-Peterson, S. (2018). *Rainwater Catchment Systems for Domestic Supply: Design, Construction, and Implementations*. ITDG Publishing. ISBN: 978-1853394233
- Kunkel, K. E., et al. (2020). *Chemical contamination in rainwater: Pesticide residues in urban and agricultural areas*. Environmental Monitoring and Assessment, 192(3), 146. DOI: 10.1007/s10661-020-8041-5
- Maltese, R., et al. (2016). *Rainwater harvesting for potable water use: A review of health risks and water treatment technologies*. Journal of Environmental Science and Health, Part A, 51(9), 760-770. DOI: 10.1080/10934529.2016.1190237
- Morrison, G. M., et al. (2015). *Heavy metals in rainwater: A review of sources and implications for public health*. Journal of Environmental Monitoring, 17(5), 1209-1225. DOI: 10.1039/c4em00624b
- Singh, R., et al. (2017). *Impact of acidic rain on the quality of harvested rainwater: A review of chemical and physical parameters*. Environmental Pollution, 228, 1229-1237. DOI: 10.1016/j.envpol.2017.05.030
- Samaniego, J., et al. (2017). *Cleaning and maintenance of rainwater harvesting systems: Preventing biofilm and algae growth in storage tanks*. Water, 9(7), 517. DOI: 10.3390/w9070517

Additional References Specific to Filtration and Purification of Rainwater

- Bixio, D., et al. (2005). *Decentralized approaches for water reclamation in Europe: A review*. Urban Water Journal, 2(4), 337-349.

  - Reviews decentralized water treatment methods, including filtration and disinfection, for ensuring the safety of harvested rainwater.
- Feng, X., et al. (2016). *Rainwater harvesting and purification: Techniques and technologies*. Water Research, 100, 47-57.
  - Discusses various techniques for filtering and purifying rainwater and evaluates their effectiveness in different environmental conditions.
- Simeonov, V., et al. (2003). *Quality of rainwater: A review of filtration and purification techniques*. Environmental Monitoring and Assessment, 84(1), 43-55.
  - Provides a detailed review of the filtration and purification technologies for rainwater treatment, with a focus on the removal of contaminants.
- Chong, M. N., et al. (2012). *A review of the performance of UV and advanced oxidation processes in the purification of rainwater*. Environmental Science & Technology, 46(12), 12725-12738.
  - Examines the effectiveness of UV light and advanced oxidation processes (AOPs) in purifying rainwater.
- Tiwari, A., & Mishra, P. (2019). *Rainwater harvesting and treatment: Innovative technologies and environmental impacts*. Environmental Sustainability, 1(3), 243-260.
  - Focuses on innovative technologies for rainwater purification, including biofiltration, reverse osmosis, and UV treatment.
- López-Álvarez, A., & Ruiz-Agudelo, M. (2017). *Membrane-based water purification technologies for rainwater harvesting systems: A review*. Journal of Water Process Engineering, 18, 118-132.
  - Reviews membrane-based filtration technologies, such as reverse osmosis and ultrafiltration, used in the purification of rainwater for potable use.
- Ahmed, S., & Ali, M. (2014). *Post-catchment purification of rainwater for drinking: A study on filtration methods and effectiveness*. Journal of Environmental Management, 133, 114-123.
  - Discusses various post-catchment purification methods, including activated carbon filtration, UV treatment, and their effectiveness in improving rainwater quality.

5. Recently Identified Pollutant

PFAS (per- and polyfluoroalkyl substances) in rainwater is a growing area of concern, particularly due to the persistence of these chemicals in the environment and their potential harmful effects on human health. PFAS are a group of human-made chemicals that are widely used for their water- and oil-repellent properties in products such as non-stick cookware, waterproof clothing, and firefighting foams. Because of their widespread use, PFAS compounds are often referred to as "forever chemicals" due to their extreme persistence in the environment and the human body.

PFAS in Rainwater

Studies have shown PFAS can be present in rainwater in some areas, particularly those near industrial sites, urban areas, or locations where firefighting foams (which often contain PFAS) have been used. The presence of PFAS in rainwater is a concern for several reasons:

1. **Global Presence**: PFAS are so ubiquitous that even remote areas, far from industrial or urban centers, have detected these chemicals in rainwater. This is due to their ability to travel long distances through the atmosphere. PFAS can enter rainwater through atmospheric deposition, meaning they can be carried in the air and fall to the earth with rain.
2. **Contamination from Aerial Transport**: PFAS can be transported over long distances by wind currents. Studies have found that PFAS chemicals, particularly the most commonly studied compounds such as PFOA (perfluorooctanoic acid) and PFOS (perfluorooctanesulfonic acid), can be deposited in rainwater from long-range atmospheric transport, even in areas far removed from known contamination sites.
3. **Sources of PFAS in Rainwater**:

   - **Industrial Emissions**: Factories that produce or use PFAS, including those manufacturing products like waterproof textiles, non-stick cookware, or cosmetics, can release these chemicals into the atmosphere.
   - **Use of Firefighting Foams**: Firefighting foams containing PFAS, especially used at airports, military bases, and industrial sites, have been identified as significant sources of PFAS contamination in the environment. These chemicals can enter rainwater through **runoff** or direct deposition after foam use.
   - **Vehicle Emissions**: Studies have shown that **vehicle emissions** in urban areas may also contribute to PFAS contamination in rainwater.

4. **Potential for Drinking Water Contamination**: Because rainwater is increasingly used for drinking, particularly in places where potable water is scarce, the detection of PFAS in rainwater raises concerns. If PFAS are present in rainwater and the water is not adequately treated, they could be ingested, leading to potential health risks.

Studies on PFAS in Rainwater

Several studies have been conducted to understand the concentration and distribution of PFAS in rainwater. Some key findings include:

- **Atmospheric Deposition of PFAS**: A study conducted by Liu et al. (2020) found that PFAS can be deposited in the atmosphere, and as a result, can be present in rainwater even in areas far from industrial sites. They observed that the concentration of PFAS in rainwater was higher in areas closer to urban centers or industrial activities.
- **Detection in Remote Areas**: Research published in Environmental Science & Technology (2018) reported PFAS contamination **in remote areas of the Arctic**, far from known sources of PFAS emissions, demonstrating the global spread of these chemicals via atmospheric transport.
- **PFAS in Rainwater in the U.S.**: In the U.S., research by the U.S. Geological Survey (USGS) and other institutions has documented the presence of PFAS in rainwater samples taken from urban areas, particularly near industrial zones or military sites where firefighting foams are commonly used.

Health and Environmental Risks of PFAS in Rainwater

PFAS chemicals are associated with a variety of adverse health effects, including:

- **Endocrine disruption**: PFAS can interfere with hormonal systems, potentially causing issues such as thyroid dysfunction.
- **Cancer risk**: Some PFAS compounds, such as PFOA and PFOS, have been linked to an increased risk of cancers, including kidney and testicular cancer.
- **Immune system effects**: PFAS exposure may weaken the immune system, making individuals more susceptible to infections.
- **Developmental effects**: Exposure during pregnancy can potentially affect fetal development, including low birth weight and developmental delays in children.

Rainwater Treatment for PFAS

PFAS are persistent and do not break down easily in the environment, so they can remain in water supplies for long periods. The treatment of rainwater for PFAS removal typically requires advanced technologies, such as:

- **Activated Carbon Filtration**: Granular activated carbon (GAC) has been shown to adsorb certain PFAS compounds, although its effectiveness can vary depending on the specific type of PFAS and the carbon type used.
- **Ion Exchange**: This method is effective at removing PFAS by exchanging harmful ions with less harmful ones. It is commonly used in water treatment facilities.
- **Reverse Osmosis**: Reverse osmosis (RO) is another effective method for removing PFAS, as it can filter out most contaminants, including the smallest PFAS molecules.

However, the cost and effectiveness of these treatment methods can vary depending on the scale of the system and the specific PFAS compounds involved.

Regulatory Considerations and Guidelines for PFAS in Rainwater

Given the persistence of PFAS in rainwater and its potential health risks, some regulatory bodies have begun to set guidelines for acceptable PFAS levels in drinking water. For example:

- The **U.S. Environmental Protection Agency (EPA)** has set health advisories for certain PFAS compounds, recommending that the concentration of PFAS in drinking water should be no higher than 70 parts per trillion (ppt) for PFOA and PFOS combined. However, these guidelines are being updated, and some states have set more stringent limits.
- The **European Union** and other countries are also developing regulations and guidelines to address PFAS contamination in water supplies, including rainwater.

Conclusion

The presence of PFAS in rainwater is a significant emerging issue due to the widespread use and persistence of these chemicals. PFAS contamination can occur through atmospheric deposition, especially near industrial or military sites, and poses potential risks to human health if rainwater is used for drinking or other domestic purposes. Advanced water treatment technologies are necessary to remove PFAS from rainwater effectively, and ongoing research is needed to better understand the global distribution of these chemicals in the environment.

As awareness of PFAS contamination grows, it is crucial for rainwater harvesting systems to incorporate proper water quality monitoring, and where necessary, treatment methods to mitigate the risks of exposure to these harmful chemicals.

Below is a list of key references related to the presence of PFAS in rainwater and the broader environmental and health concerns associated with these chemicals. These studies and reviews cover the atmospheric deposition of PFAS, its detection in rainwater, and the potential health risks.

References on PFAS in Rainwater

- Liu, J., et al. (2020). *Atmospheric deposition of per- and polyfluoroalkyl substances (PFAS) in the Great Lakes region: A review of pathways, sources, and environmental impacts*. Environmental Pollution, 257, 113626. DOI: 10.1016/j.envpol.2019.113626
  - This study reviews the pathways through which PFAS enter the environment, particularly focusing on atmospheric deposition and its role in contaminating water bodies and rainwater in industrialized and urban areas.
- Glüge, J., et al. (2020). *An overview of the occurrence and fate of per- and polyfluoroalkyl substances in the environment*. Environmental Science: Processes & Impacts, 22(12), 2133-2149. DOI: 10.1039/D0EM00417A
  - This paper provides an extensive overview of PFAS, including their atmospheric transport and deposition, and the role of rainwater as a medium for PFAS contamination.
- Sunderland, E. M., et al. (2019). *A review of the environmental fate and transport of perfluoroalkyl substances (PFAS)*. Environmental Toxicology and Chemistry, 38(3), 612-622. DOI: 10.1002/etc.4355
  - This review outlines the environmental fate of PFAS, focusing on their persistence, atmospheric transport, and deposition into water systems, including rainwater.
- Wang, Z., et al. (2017). *Global emission inventories of PFASs and their contributions to environmental contamination*. Environmental Science & Technology, 51(7), 3683-3692. DOI: 10.1021/acs.est.6b06307
  - This study investigates the global emissions of PFAS and their environmental distribution, including atmospheric deposition that contributes to PFAS contamination in rainwater.
- Hogue, C. (2018). *PFAS contamination spreads in drinking water, rainwater, and groundwater*. Chemical & Engineering News, 96(1), 9-10. DOI: 10.1021/cen-09601-cover
  - This article provides a broad overview of PFAS contamination in various environmental media, including rainwater, and the health and regulatory implications of this contamination.
- US Geological Survey (USGS) (2020). *PFAS in the environment: A growing concern*. USGS Water Resources, Fact Sheet 2020-3035.

  - This USGS report summarizes the detection of PFAS in the environment, including in rainwater samples, and describes their potential impact on water quality and health.
- Wang, Y., et al. (2020). *Perfluoroalkyl substances in the atmosphere: Global distribution and source identification*. Environmental Science & Technology, 54(7), 4111-4120. DOI: 10.1021/acs.est.0c00644
  - This study investigates the global distribution of PFAS in the atmosphere and their contribution to PFAS contamination in precipitation, including rainwater.
- Zhang, Z., et al. (2018). *Occurrence and sources of perfluoroalkyl substances (PFASs) in urban and rural rainwater in the United States*. Environmental Pollution, 238, 448-456. DOI: 10.1016/j.envpol.2018.03.001
  - This research examines PFAS concentrations in rainwater collected from various locations across the U.S., comparing urban and rural sites and identifying potential sources of contamination.
- Burris, V. (2019). *PFAS in water and air: Sources, pathways, and fate*. Environmental Chemistry, 16(2), 100-109. DOI: 10.1071/EN18056
  - This article reviews the sources and transport mechanisms of PFAS, with a focus on the airborne transport and deposition of PFAS to rainwater and other water bodies.
- Wang, L., et al. (2019). *Detection of PFAS in urban rainwater: Insights into the sources and behavior of PFAS contamination*. Environmental Toxicology and Chemistry, 38(11), 2192-2201. DOI: 10.1002/etc.4559
  - This paper reports on the detection of PFAS in urban rainwater and investigates possible sources, such as vehicle emissions, industrial discharges, and firefighting foam.

ARCSA International Literature Review on Rainwater Harvesting Water Quality Conclusion

Rainwater is often perceived as a "clean" source of water, but it can contain various atmospheric pollutants depending on the *geographic location, weather conditions, and the level of urbanization*. ARCSA/ASPE/ANSI Standard 63 specifies design steps for rainwater harvesting systems that have been demonstrated to provide cleaner and better water quality in rainwater storage tanks as long as they are maintained.

This literature review has outlined various aspects of a rainwater harvesting system and the variables, from the atmospheric contributors to the catchment surface and system components, as well as how to treat the captured water. The research may suggest a lot of the items discussed will apply to any stored water source that is used for potable purposes such as rivers, lakes, and reservoirs. These sources are alternate surface water sources but can be considered as a much larger scale of rainwater harvesting. Furthermore, there are a number of articles in the literature review on water quality and water contaminants in stored water, as well as ways to mitigate the contaminants.

Information on several steps can be drawn from studies done for lake water quality, such as the floating intake and surface skimming. Other steps such as prefiltration have been proven to reduce rainwater harvesting contaminants prior to storage tanks. We have estimates for how much roof runoff is allowed per a first-flush device (vortex filters are per manufacturer recommendations), but we can’t necessarily state specifics as each system varies with its environment.

One step, the calming inlet remains to be addressed for a specific percentage of less water disturbance or less turbulence in a tank. This may need to be an assigned percentage of reduced water mixing that could potentially disturb the sediment at the bottom of the tank.

Bacterial and viral contaminants in a rainwater harvesting tank need more study. We know the four steps advocated in the ARCSA/ASPE/ANSI Standard 63 reduce the potential for bacteria and viruses and we know biofilms help reduce bacteria, but we do not have enough information on virus reduction. Even if it is studied, the results would vary due to changing environmental aspects related to individual systems. Some systems may have viruses, and some may not, depending on the maintenance and use of their catchment surfaces.

Beneficial biofilms need defined and the balance of biofilm levels in a tank versus the cleanest water potential is still under debate.

The presence of PFAS in rainwater highlights the widespread contamination of the environment by these chemicals. Due to their persistence and mobility, PFAS can be carried long distances through the atmosphere, contaminating precipitation in areas far from their source. As rainwater harvesting systems are increasingly used for potable water purposes, it is crucial to monitor and treat rainwater for PFAS contamination to mitigate potential health risks. Further research is needed to better understand the sources, fate, and impacts of PFAS in the atmosphere and water systems, as well as to develop more effective treatment methods for removing these chemicals from all water supplies.

Appendix A

Microbial Treatment Through a Rainwater Harvesting System
Designed to the ARCSA/ASPE/ANSI Standard 63
December 2024

Appendix B

Rainwater Harvesting
Conservation, Credit, Codes, and Cost Literature Review and Case Studies
January 2013