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Research paper

Exploring the Potential of Rainwater Harvesting for Cooling Towers: A Systematic Review and Regional Feasibility Assessment

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ABSTRACT

Water scarcity has driven interest in rainwater harvesting, especially for U.S. industries like power and manufacturing, which dedicate a large percentage of their water needs to cooling towers. This paper provides a comprehensive systematic review of studies on the use of rainwater in cooling tower applications, along with an assessment of the regional feasibility of integrating RWH in U.S. manufacturing cooling towers. The systematic review examines the technical, economic, environmental, and policy feasibility of utilizing harvested rainwater, and the regional feasibility analysis evaluates the practical implementation of RWH in manufacturing cooling towers, considering factors such as regional RWH potential, water costs, state policies, and the industrial water use of manufacturing facilities per state. This study supports the hypothesis that RWH for cooling towers is technically feasible, economically viable, and environmentally beneficial. Harvested rainwater is naturally less conductive and soft, and rainwater reuse minimizes the ecological footprint. Supportive state policies, regional RWH potential, and rising water costs across the U.S. are important variables that may impact RWH adoption. The review highlights rooftop RWH as the most studied method and notes that implementing RWH requires infrastructure changes and filtration techniques. While initial investment costs may be high, operational and maintenance costs are low, making RWHS economically feasible over time. Regions with higher water costs and supportive policies are more likely to benefit from RWH adoption. The study provides a foundation for understanding the potential for using RWH in industrial cooling towers.

1. Introduction

Water scarcity has emerged as a critical global issue for the past few decades, stemming from causes such as increasing population, growing water demand for domestic, industrial, and technological uses, as well as data centers. In response, researchers have investigated various alternatives to decrease reliance on potable freshwater, including water reuse and recycling, reclaimed water, desalination, rainwater harvesting (RWH), and greywater reuse. Of these alternatives, RWH has drawn significant attention as an effective solution to reduce dependence on freshwater for many applications. This technology has been investigated as a substitute for freshwater use in water stressed regions [1–4], with research ranging from using machine learning for feasibility assessment to real-world cases studies. García-Ávila, et al. [4], for example, conducted a systematic review on the use of RWH for water scarce regions and found that this approach is an effective solution for water supply in rural and water scarce regions as long as the technologies are properly implemented and maintained. RWH has also been studied for a variety of applications, including in commercial [5–10] and residential [11–24] buildings. Matos, et al. [5] evaluated the most cost-efficient RWH system for a new commercial building in northern Portugal. Lima, et al. [12] assessed the economic viability of implementing rainwater harvesting in residential condominiums in the Brazilian Midwest city of Campo Grande, focusing on collection methods paired with suitable treatment for non-potable applications. Halder et. al [1] indicated rainfall and runoff potential as crucial factors in selecting suitable locations for RWH in urban and rural areas. Finally, Ortiz, et al. [24] analyzed the technical and economic impacts of RWH systems for domestic applications concluding that while RWH is technically effective for conserving water and mitigating flooding, its economic validity heavily relies on the local price of public water.

More recently, RWH has also been evaluated for industrial

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applications [25–29], such as for concrete production, petrochemical manufacturing, and building construction sites. In all these applications, RWH is defined as the collection of rainwater from rooftop surfaces or other surfaces and not stormwater runoff that is not absorbed into the ground [30]. RWH in the industrial sector is particularly relevant, because industries in the U.S. and globally account for a substantial portion of total water consumption [31]. The sector that consumes the most water in the U.S. is thermoelectric power generation, accounting for 49% of total water use followed by agriculture at 36%, domestic use at 8%, and the manufacturing sector at 6% [31,32]. Manufacturing water withdrawals in 2015 were about 14,800 Mgal/d, with most of the self-supplied water withdrawals being from freshwater sources [33]. These sectors offer a valuable opportunity for rainwater use in non-potable purposes. A large percentage of industrial, domestic, and manufacturing water consumption is dedicated for cooling tower use [34]. Cooling towers are essential in refrigeration systems as they provide cooling for a variety of applications, they can be found in residential cases providing air conditioning or different industrial processes in manufacturing and industrial uses to regulate temperature [34]. EPA estimates cooling towers represent 20-50 percent of a commercial and institutional facility's total water use [35]. Therefore, using rainwater in cooling towers can be a valuable avenue for reducing dependence on freshwater use as global supplies of freshwater become more and more limited with increasing costs. The harvesting and use of rainwater in cooling towers can help alleviate the use of a large portion of freshwater in manufacturing applications providing decreased water costs and water footprint. This study provides the first systematic literature review of RWH for cooling towers, combined with a novel regional feasibility analysis.

Cooling tower systems provide cooling to industrial, commercial, and residential facilities and are an integral part of the heat rejection system for manufacturing processes, space conditioning, and refrigeration systems [34,36]. Cooling towers are key components to the cooling system, along with the recirculating pumps, piping network, and heat exchangers. Cold water from the bottom of the cooling tower or basin picks up the heat from the heat exchanger and drops it from the top of the cooling tower [34]. Cooling towers distribute the hot water from the processes or mechanical room over a fill material from the top of the cooling tower, where air evaporates some portion of water while absorbing heat, expelling warm, moist air into the air and cooling down the remaining water in the tank [34,37]. Cooling towers are designed to maximize this contact of air and water, providing cooling from the resulting evaporation [34]. Even though cooling towers recirculate the water within the cooling system, water can be expelled through evaporation, blowdown or bleed-off, leaks or overflows, and drift [37]. As the basin water level drops due to the cyclical cooling and evaporation of water, fresh make-up water is added to restore water levels in the cooling system. Evaporated water leaves behind dissolved impurities in the cooling system and is considered detrimental to the system performance and equipment, and can lead to scaling and corrosion within the cooling systems [34]. According to the EPA, for every 10°F in temperature drop achieved by the cooling tower, about 1 percent of the recirculating water flow is lost to evaporation. This is equivalent to roughly 1.8 gallons of water evaporated per ton-hour of cooling provided [35,37,38]. Higher concentrations of minerals such as calcium, magnesium, chloride, and silica, etc. can be detrimental to the cooling tower components and cause system inefficiencies. The process of removing portions of the water with higher concentrations of total dissolved solids (TDS) is referred as blowdown or bleed-off. Drift losses range from 0.05% to 0.2% (0.24-0.36 gallons per ton-hour) of the cooling tower's flow rate and occur when tiny droplets or mist are released from a cooling tower [35].

Many scholars have evaluated the use of rainwater in cooling applications; however, the majority have focused on assessing the use of the harvested rainwater in space cooling such as for households or residential buildings [39–43], schools [44], and universities [45,46]. The system proposed by Venkiteswaran, et al. [46] was highly novel, consisting of a flowing harvested rainwater wall positioned between two layers of a glass façade. Its primary function was to dissipate heat accumulated on the glass while allowing light to pass through. The study demonstrated that, for the school building examined, the system could save a total of 658.972 kWh per month. Other scholars have studied the controls, optimization or storage tank sizing of cooling towers [47–50]. Hilmi and Khalid [48] used Tanki NAHRIM 2.0 to assess the performance of different storage tank sizes in terms of maximizing water savings and system reliability. Guo and Baetz [49] developed a set of analytical equations to determine the rainwater storage volume needed, taking into account the intended water demand, reliability requirements, and local climatic conditions. There has also been an interest in using rainwater for the manufacturing industry; Bertuzzi and Ghisi [25] investigated the use of rainwater for the water demands of a Brazilian precast concrete factory and found that rainwater was a suitable alternate resource to produce concrete for their specific case study, even concluding that it was of adequate quality for the purpose of concrete manufacturing and discussed financial feasibility options [25]. Similarly, in another study conducted in the water stressed region of Nigeria, Ogwu, et al. [28] found that harvested rainwater covers 99% of the water demand of the studied manufacturing establishment with a 1.6 years simple payback period. However, only two studies were found that investigated the use of rainwater in cooling towers. Cejudo et. al [30] reviewed alternative water resources for cooling towers and reported that RWH systems (RWHS) would require minimal infrastructure as compared to other water resources. They show that rainwater would be of medium water quality thus needing screening to remove large particles, a filtration method, and depending on the situation, disinfection [30]. Thomé, et al. [26] on the other hand specifically evaluated the use of harvested rainwater in the cooling towers of a petrochemical company in Brazil and concluded that the use of rainwater for this purpose is viable. They showed that the quality of rainwater is acceptable once the stored water has been treated using the chlorinator and cartridge filter for the use in cooling towers and provided proof of economic feasibility [26]. Figure 1 illustrates the RWH flowchart used to supply water for cooling tower operations, highlighting how collected rainwater is captured, and treated if necessary.

While existing literature on RWH primarily addresses residential, domestic, and general manufacturing applications, its specific use in cooling towers remains largely unexplored. A systematic review is therefore essential to consolidate and critically evaluate the current body of knowledge on RWH in industrial contexts, particularly for cooling towers. This study addresses this challenge by providing a systematic review of RWH for cooling towers, coupled with regional feasibility analysis for using harvested rainwater as makeup water in cooling tower system operations. The objectives of this paper are twofold: first, to conduct a comprehensive systematic review to identify all relevant studies addressing the use of rainwater in cooling tower applications; and second, to assess the regional feasibility of integrating RWH in cooling towers in the U.S. manufacturing sector. The systematic review will examine the technical, economic, environmental, and policy feasibility of utilizing harvested rainwater in this context. More specifically, the systematic review will aim to provide insights regarding rainwater use in cooling towers based on the following questions:

1. Technical feasibility
    - What RWH technologies are discussed in existing literature?
    - How does the use of rainwater impact the operation of cooling towers? And, what are the RWH applications discussed (which sector or facilities are best aligned to utilize RWH technologies)?
    - Are modifications required to existing cooling tower infrastructure to utilize RWH technology?
    - Is there discussion related to precipitation or RWH potential?
    - How feasible is using rainwater in cooling towers in the manufacturing sector? If so, what kind of treatment is required?

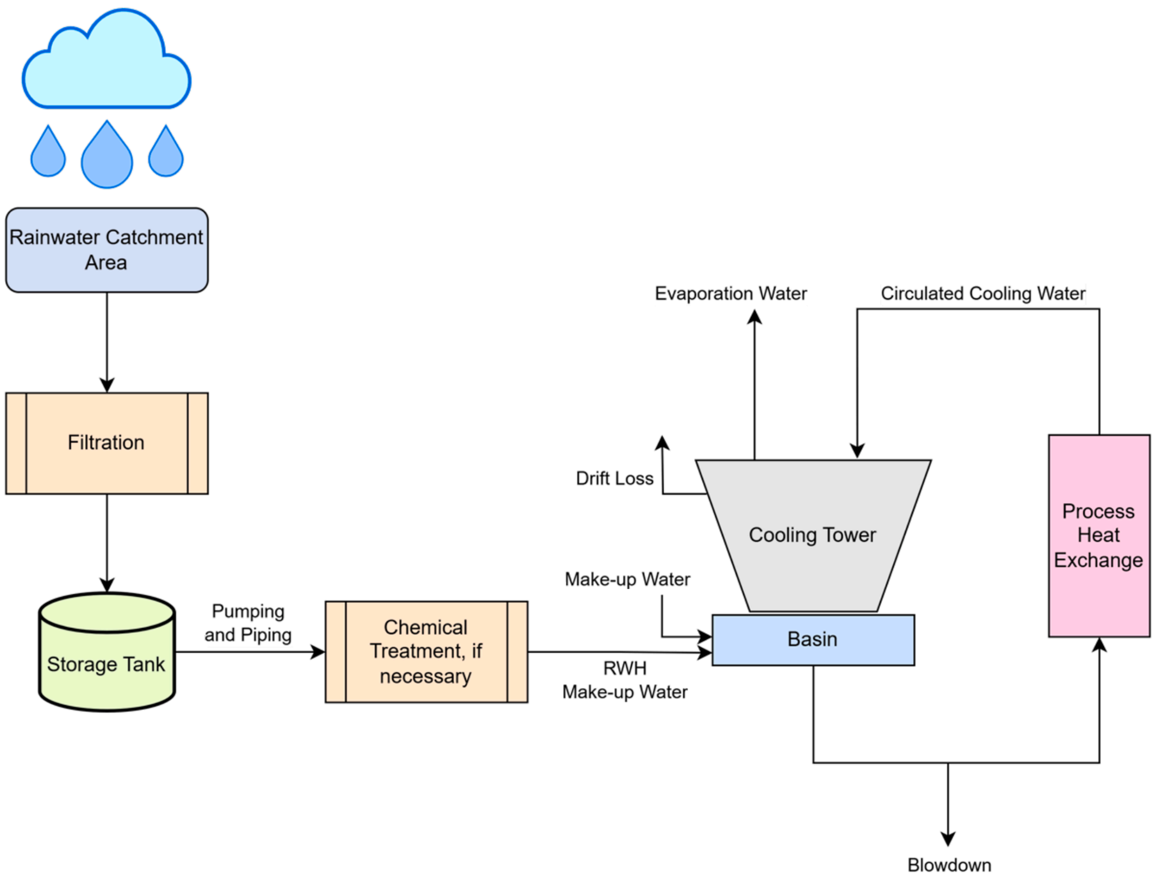

Figure 1. Overview of rainwater harvesting for cooling tower water needs.

2. Economic Feasibility
   - What are the long-term costs and maintenance implications of using rainwater in cooling towers?
   - What are the costs versus savings tradeoffs of using RWH in cooling towers?
   - How does the price of water and resource availability affect the reuse of rainwater in the manufacturing sector?
3. Environmental Feasibility
   - What are the environmental impacts of using harvested rainwater?
   - Does energy demand increase with RWH and use?
   - Is there any analysis about avoided emissions related to the use of harvested rainwater?
4. Policy Feasibility
   - What are the regulations around using rainwater for cooling tower or process applications in the US?
   - Is there discussion related to policies/standards for rainwater use in cooling towers?
   - Are there other policy related implications?

Additionally, the regional feasibility analysis will evaluate the practical implementation of RWH in manufacturing cooling towers, considering factors such as regional RWH potential patterns, water costs, state-specific policies, and the industrial water use of manufacturing facilities per state. By exploring RWH and application to cooling towers, and the regional viability of their implementation, this paper contributes valuable insights for advancing alternative water resource use in the U.S. manufacturing sector.

2. Methods

This analysis followed a mixed methods approach. A systematic review of the literature was conducted followed by a regional feasibility analysis.

2.1. Systematic Literature Review

The systematic review of the literature followed the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) [51] standards which is a set of guidelines created for conducting systematic reviews. For comprehensive details related to the PRISMA methodology, please refer to Page, et al. [51]. To collect data of the systematic review, bibliographic databases Web of Science and Scopus were used to retrieve articles relevant to the use of RWH for cooling towers as well as Google Scholar. The search strings and keywords used for the database searches were (1) “rainwater” or “rain water” or “rain-water” and “cooling towers” or “cooling tower” with a total of 331 articles extracted from the 3 databases, (2) “rainwater” or “rain water” or “rain-water” and “manufactur*” with a total 541 articles extracted, and (3) “rainwater “or “rain water” or “rain-water” and “cooling systems” or “cooling system” or “cooling-systems” or “cooling-system” with a total of 565 articles. The Supplementary Information (SI) Table 1 summarizes each of the search strings per database with the number of articles retrieved for each. This collection of the data from the databases was done on October 22, 2024. For the inclusion and exclusion criteria of articles collection, there was no specified range for the dates that the articles were published. All articles available in the databases by the day

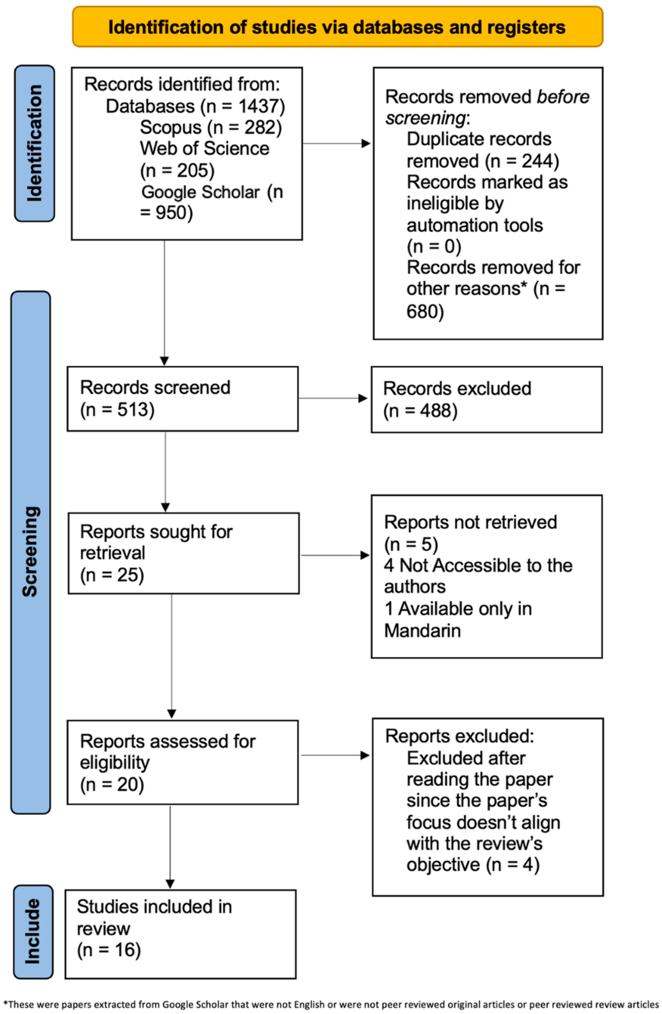

Figure 2. The PRISMA guidelines-based flowchart illustrating the retrieval and screening of the articles.

of the data collection were retrieved. The research inclusion criteria included articles in English and the following publication types: articles, review papers, or conference papers from Scopus and Web of Science. Due to the high volume of results, only original articles and review papers were included from Google Scholar. Excluded from the analysis are book chapters, non- peer reviewed articles and reports, and conference reviews.

A total of 1437 articles were extracted from the databases. Then, the duplicates were removed, and we ensured that all the articles met the inclusion criteria, and we had 513 articles for analysis. Two of the authors (AB and IB) individually screened each of the 513 articles to decide whether each paper should be included in the systematic review or not based on the research questions being addressed by this review. Then, the authors convened to discuss any articles with differing decisions and collaborated to reach a consensus on their inclusion. SI Table 2 represents the decision votes and corresponding notes regarding the exclusion of any paper. After the voting process, 25 articles were voted to be in the review assessment. Therefore, 25 articles were retrieved for review. Of the 25 articles, 4 were not accessible to the authors and 1 was only available in mandarin, consequently we retrieved and reviewed 20 articles. After reviewing the 20 articles, 4 more articles were excluded as they were not in sync with the objective of the review and focused on other aspects of rainwater use in cooling applications. Figure 2 summarizes the PRISMA guidelines-based flowchart illustrating the retrieval and screening of the articles. A total of 16 articles were reviewed for this analysis. To evaluate the articles, a comprehensive assessment of the information related to the technical, environmental, economic, and policy feasibility was conducted.

2.2. *Regional Feasibility Analysis*

As for the regional feasibility analysis, the objective was to evaluate the viability of using harvested rainwater for cooling towers in the U.S. To conduct this assessment, a broad scope regional feasibility analysis was followed focusing on four main aspects (1) RWH policies per state [52,53], (2) RWH potential per state [53], (3) water costs [54], and (4) the total self-supplied water per state for industrial use [33]. First, state policies related to RWH, and use were assessed and divided into categories of whether they facilitate or hinder the use of rainwater in manufacturing applications and specifically for cooling towers. Then, it was investigated whether the RWH potential per state could meet the demand of the industrial water demand per facilities and the water costs per state were analyzed to identify regions where RWH would be viable. Finally, a multi-layered map was created to visually highlight regions where RWH is more feasible and preferred, compared to areas where it may be more challenging to implement.

3. Results and Discussion

This section presents the results of the systematic review and regional feasibility analysis and discusses these findings in relation to other studies.

3.1. *Systematic Review Results*

3.1.1. *Technical Feasibility*

RWH involves collecting rainwater to provide alternative sources to supplement non-potable and potable water needs. The technical feasibility of RWHS consists of the technologies used, the application of rainwater, the required conditions for the quality of the rainwater, and modifications required for incorporating RWH in the facility. In this section, the aim was to identify from the literature reviewed the following:

- RWH technologies,
- Applications for harvested rainwater,
- Impact of rainwater usage on cooling towers,
- Modifications and changes required to incorporate rainwater,
- RWH potential or precipitation levels needed, and
- Rainwater treatment methodology.

The current literature presents various ways to harvest rainwater from rooftops and store it for different purposes, including cooling tower makeup [55]. Since rainwater is soft and low in dissolved solids, it may be recirculated multiple times in the cooling tower before discharge, reducing water waste [28]. Current literature explores various methods of harvesting rainwater for numerous applications including but not limited to grey water use, manufacturing processes, non-potable water, and others. However, there is a lack of sufficient material and research dedicated to reuse of harvested rainwater as makeup water for cooling towers, especially in industrial and manufacturing sectors. Table 1 summarizes the main results from the technical feasibility highlighting the main technologies discussed in the reviewed papers, the application of rainwater, impacts on cooling towers, changes needed for the system, measures for RWH potential and treatments/filtration methods used for filtering the rainwater.

Table 1
Technical feasibility analysis of articles in review.

Technology Aspect	Key Details	References
Technologies	Rooftop collection	[25,26,28,38,55,57,58,62,64,65,67,68]
	Storage (cisterns, tanks, reservoirs, wells)	[25,26,28,38,57,58,62–64]
	Storage (deep lakes, ponds)	[65]
Sector Or Application Suitability	Cooling tower makeup water	[26,38,55,57]
	Non-potable water (non-manufacturing)	[25,28,55,57,62–65,68]
	Non-potable water (manufacturing)	[25,28,65]
	Grey water	[61,63,64]
	Potable water	[55,68]
	Power generation (Cogen)	[64,67]
Impact On Cooling Towers	Increased cycles of concentration (COC)	[57]
	Corrosion limits in carbon steel	[26]
Modifications	Storage tanks, cisterns, reservoirs, wells	[25,26,28,57,58,62–64,68]
	Piping	[25,28,57,58,62,64,68]
	Gutters	[25,28,58]
	Filtration system	[57]
	Pumps and valves	[26,58,64]
Rwh Potential	Precipitation, rainfall records	[25,26,28,55,57,58,62–65,67,68]
	Catchment area	[25,26,28,38,55,57,58,62,63,65,67]
	Climate descriptions	[25,55,57,62]
	Simulation models, calculated	[63,64,67]
Treatment And Tests	Filtration, screening	[26,57,58,62,64,65,68]
	TDS and COC	[57]
	First flush	[25,57]
	Activated carbon	[66,68]
	Chlorination	[26,58,64,68]
	UV Disinfection	[64]
	Ionic exchange	[65]
	Carbide removal	[65]
	Limewater	[65]
	Other chemicals	[38,58]

3.1.1.1. Technologies. The analysis shows that the majority (13) of the articles discussed rooftop RWH methods as primary technology for collecting rainwater. Rooftop and catchment harvesting is one of the primary ways of collecting rainwater along with harvesting with underground cisterns and tanks [56]. Nine articles, Bian, et al. [57], Ogwu, et al. [28], Shiguang, et al. [58], Betz and Kuh [38],Thomé, et al. [26], Ahmed, et al. [59], Cook, et al. [60], and de Gois, et al. [61] discussed the use of storage units such as tanks and cisterns focusing on their usage during times of need. Ogwu, et al. [28], Shiguang, et al. [58], Matos, et al. [62], and Borges, et al. [63] discussed in brief that the volume of the cisterns required is proportional with water demand, precipitation, and the catchment area or the area under study. Ahmed, et al. [59] proposed that the tank size required is inversely proportional to the amount of rainfall received and it is the harvesting or catchment area that determines the amount of water being added whenever it rains. The study discusses the constraint on the minimum tank size for a feasible catchment area, suggesting a saturation of benefits from larger tank capacities, primarily due to the intermittent nature of rainfall. Local rainfall patterns, cost of tap water, and the estimated construction expenses for a RWHS also determine the cistern volumes [28,58]. Ogwu, et al. [28] employed rooftop RWH using rainwater barrels to store the collected water for manufacturing and non-potable use at a small-scale facility in Nigeria. A case study from Portugal [62] evaluated non-manufacturing and non-potable water end-use such as greywater systems, cooling towers, carwashes, boilers and HVAC systems for manufacturing and industrial facilities using simulation models for several storage volumes [62]. Borges, et al. [63] discussed their simulation model using the computer program Neptune 4.0, developed by LabEEE (Laboratory of Energy Efficiency in Buildings) of the Federal University of Santa Catarina, Brazil. The simulation tested the generated savings in drinking water verified against various sizes of the reservoir [63]. The study also considered the runoff coefficient for determining the volume of the rainwater to be collected.

Other storage mechanisms mentioned were reservoirs (Matos, et al. [62], Borges, et al. [63], Sousa, et al. [64], and Novaes and De Oliveira Cachuté [65]), and wells (Bertuzzi and Ghisi [25]). Three articles did not mention any rainwater storage technologies throughout the manuscripts. Bertuzzi and Ghisi [25] evaluate the use of rainwater in the manufacturing and cleaning applications at a precast concrete factory in southern Brazil. They store the collected rainwater in wells and the potential for water savings using different storage capacities is simulated based on future demands of the facility. Betz and Kuh [38] proposed deep lake storage reservoirs for providing an alternative source of non-potable water for manufacturing and non-manufacturing processes at a carmaker in Brazil. Although not considered in the literature review, Liu, et al. [66] discussed rooftop harvesting storage tanks as well as managing stormwater using aquifers and groundwater tables in their thesis. They discussed that it is important to consider the ratio of tank volume (V) to the catchment area (A) to determine either the harvesting area or the calculation of tank volumes. Rainwater Use efficiency or RUE will also determine how often the rainwater being harvested is utilized in applications such as cooling tower makeup water. The thesis also discussed that the selection of the rooftop materials will depend on the application of harvested rainwater, and even concrete tiles may be selected for collecting water for cooling tower makeup water purposes [66]. These results show that rooftop RWH is clearly the prevalent technique utilized for collecting rainwater around the world for various purposes and reuse of harvested rainwater is possible in cooling towers.

3.1.1.2. Application and Impact on Cooling Towers. The main focus of the systematic literature review was to investigate whether rainwater can be used in cooling towers at manufacturing facilities. The majority of the articles (11), however, did not explicitly discuss this application. Cook, et al. [60] does not directly mention the use of rainwater as cooling tower makeup water but discusses a case study of commercial buildings in Australia where the recovered condensate from air handling units (AHU) is being used in cooling towers. Similarly, Borges, et al. [63] does not explicitly mention the use of harvested rainwater in cooling towers, but does consider using rainwater to cut-down the dependence on non-potable water applications. Cooling towers are considered one of the major users for non-potable water in the case study focused on commercial building (shopping complex located in Brazil). Loper, et al. [55], Sousa, et al. [64], Betz and Kuh [38], and Thomé, et al. [26] discuss using harvested rainwater to supplement the makeup water for cooling towers in the facility. Bian, et al. [57], Loper, et al. [55], Betz and Kuh [38], and Thomé, et al. [26] clearly discuss utilizing rainwater to makeup the evaporation losses occurring in the cooling towers. Whereas Sousa, et al. [64] discuss reutilizing the harvested rainwater for supplying the cogeneration plant condensation circuit for providing cooling to chillers, but are a little unclear whether they are directly supplying the collected rainwater to the cooling towers of the chillers, in addition to supplying the cogeneration plant. Moreover, Ahmed, et al. [59] discusses the use of harvested rainwater in the air-side economizers to cool datacenters in cool climate regions using outside air in combination with evaporative cooling systems, other than cooling towers. These studies therefore show that it is feasible to use harvested rainwater in cooling systems [59], including cooling towers. It is suitable to use harvested rainwater for this application due to the low conductivity of rainwater, making it suitable replacement for tap water [28,57,64].

On the other hand, Bian, et al. [57] focus on using rainwater collected from large solar panel canopies in cooling towers due to evaporative losses. They find that evaporative losses lead to buildup of minerals in the cooling tower water system loop, which can cause scaling, decrease the efficacy of heat exchange, and often result in damage to the system. The water quality tests performed demonstrate that rainwater had lower total dissolved solid concentration when compared to tap-water, indicating an increase in cycle of concentrations and reduced blowdown rate [57]. Total dissolved solid (TDS) is a critical parameter for water quality test for cooling tower. TDS is also a key factor in calculating the cycles of concentration (COC), and subsequently blowdown rate. Lower TDS concentration in the blended water source results in a higher COC value [57]. Similarly, although, Thomé, et al. [26] discuss slightly higher corrosion rate whilst using carbon steel in RWHS it remained within the operational tolerance. Overall, the studies show that there are no concerns using rainwater as makeup water for the cooling towers [57,64]. Thomé, et al. [26] also claim that the addition of rainwater does not alter the composition of makeup and cooling tower water quality beyond permissible limits as per the industrial standards in Brazil. That study also reported that the pH (8.0), water hardness (170 ppm), calcium hardness (170 ppm), magnesium hardness (95 ppm), chlorides (495 ppm), turbidity, and conductivity were all under the maximum limits. They also consider fouling while evaluating replacing clarified water with rainwater and report no significant problems arising during operations or inspections [26]. Use of rainwater as cooling tower makeup water is possible as per the review study findings; however, we are aware that Liu, et al. [66], in their thesis, also studied this topic in a more detailed way and found that as long as the COC is maintained at six or higher, cooling tower will continue to operate under normal conditions. Rooftop water is preferred over water from runoff collection due to its better quality and presence of less impurities [66].

3.1.1.3. Modifications. Adoption of RWHS within a facility would require some modifications to the existing system. Loper, et al. [55], James, et al. [67], Sousa, et al. [64], Matos, et al. [62], Novaes and De Oliveira Cachuté [65], Ahmed, et al. [59], Borges, et al. [63], and de Gois, et al. [61] did not discuss the impacts of rainwater on pumping and piping equipment. As mentioned previously, the majority of the articles evaluated rooftop RWHS, mostly with storage capacity for the collected rainwater. These systems are simple yet require a number of modifications to be made to the piping and pumping network like adding pumping system, piping adjustments, and rain barrels, [28]. Relevant information about the modifications needed when adopting RWH was provided by nine articles in this review (Bian, et al. [57], Quon and Jiang [68], Shiguang, et al. [58], Sousa, et al. [64], Bertuzzi and Ghisi [25], Matos, et al. [62], Thomé, et al. [26], Shiguang, et al. [58] and Bertuzzi and Ghisi [25]) also mentioned the requirement of gutters and valves into the RWHS and extended piping to the reservoirs. The reviewed articles' results related to the modifications required to the infrastructure show that some modifications are inherent and subjective to the type of system the facility is working with. Therefore, depending on the type of technology adopted, and the purpose of rainwater use, certain changes will be required. This review did not uncover thorough details about these changes and therefore the suggestion is that more studies should investigate and identify what specific modifications will be needed.

3.1.1.4. Precipitation and RWH Potential. Next, the reviewed articles were investigated regarding RWH potential discussions and how they measured it. The analysis shows that RWH potential can be evaluated as a function of regional precipitation levels [25,26,28,55,57,58,62,64,65,67,68] and available catchment area [25,26,28,38,55,57,58,62,65,67,68] or simulated using the annual rainfall or historic climate data [38,58,62,64,67]; see Table 1. For example, the study location for Bian, et al. [57] categorizes Miami-Dade County, Florida, to have a wet season with high rainfall and constant space conditioning requirement. It utilizes local daily rainfall levels, catchment area, and rainfall frequency records from the period between 1948 and 2017 to determine the rainfall intensity and probability of volume of rainwater harvested under various hydrological wet, normal, and dry year conditions [57]. Ogwu, et al. [28], James, et al. [67], Sousa, et al. [64], Matos, et al. [62], de Gois, et al. [61], Ahmed, et al. [59], and Borges, et al. [63] use precipitation data and the available catchment area to determine the RWH potential. Therefore, the total RWH potential is a function of annual rainfall, the catchment area, and the collection efficiency of the system utilized [28,62]. The simulation conducted in de Gois, et al. [61] represents the daily volume of reusable rainwater as a product of the daily precipitation, collection or catchment area, and runoff coefficient, typically 0.95. Quon and Jiang [68] developed quantitative models to estimate the balance of quantity of harvested rainwater with water demand to appropriately size the storage and design. They reviewed the use of empirical observations or stochastic rainfall analysis to model water use and the associated system design. Loper, et al. [55] evaluated models to present information on RWH potential in a GIS format that is intended for large scale commercial and institutional portfolios management of multiple RWH projects. They also studied prior research that applied data analysis, simulation, and modelling, or GIS mapping and imaging to study RWH potential in the U.S [55]. The tool referenced in Loper, et al. [55] estimated rainwater potential for each U.S. ZIP code by considering total precipitation during frost-free months, receiving a minimum of 2.5 cm (1 in.) of rainfall in a month. These months were identified based on typical last spring frost and first fall frost dates [55]. Shiguang, et al. [58] simulated RWH potential for 236 public buildings located in the Guangzhou municipality in China, a region with historically high rainfall, using various defining factors such as catchment areas, floor areas, number of inhabitants, and non-potable demand. They also considered data from Guangzhou National Basic Meteorological Station taking into account how long it typically rains and the changes in water demand by season to accurately model the optimal systems size [58]. James, et al. [67] estimated the average daily RWH potential using roof area for new residential and commercial developments and Atlanta's average yearly precipitation over the past 30 years (49.7 inches) with an assumed collection efficiency of 0.5[67]. Sousa, et al. [64] utilized 40,000 m^2 roof area of a commercial shopping center located in Lisbon, Portugal, to collect rainwater and store it in storage reservoirs [64]. Bertuzzi and Ghisi [25] utilized the daily rainfall data for Brazil from Meteorological Database for Teaching and Research to assess the available rainfall in São José. They assumed a runoff coefficient of 0.8, as per the Brazilian standard NBR 15527[25]. Matos, et al. [62] suggest evaluating RWH potential by considering the range of precipitation between the wettest and driest years, rather than relying on multi-year averages. The case study utilizes a 2,765 m^2 rooftop area to collect rainwater for non-potable applications. They utilize SAPRA to perform a simulation of ten years using precipitation data from the National Water Resources Information System, and the meteorological station. The daily rainwater collection was calculated using the catchment area, daily precipitation, run-off coefficient of 0.8, and the filtration system hydraulic efficiency [62]. Novaes and De Oliveira Cachuté [65] estimated RWH potential for a carmaker in Rio de Janeiro, Brazil by taking into account the catchment area of 100,000 m^2 across several buildings, the rainfall in the region, and the climate in the region (tropical, with rain in the summer and drought conditions in winter) [65]. Thomé, et al. [26] utilized the average annual precipitation. Ahmed, et al. [59] models the water tank sizing using the hourly weather data and briefly discuss how rainfall data is inversely related to the size of tank required in cool or colder regions when utilized with evaporative cooling systems. de Gois, et al. [61] simulated RWH for a commercial building in Brazil, in a region with an average rainfall of 1615 mm per year. The city of Landrina, located in the region of Parana, received 1600 mm of rainfall per year between 1976 and 2013. The study found out that the longer payback on RWH systems in commercial buildings was a factor of lower precipitation in areas coincident with buildings with lower water consumption. Borges, et al. [63] included the rainfall index and precipitation between 2000 and 2020 in their model to evaluate the optimum catchment area for meeting water demands of a commercial building, while Cook, et al.

[60] did not provide details on precipitation information for the case study based in Australia.

3.1.1.5. Treatment and Tests. Harvested rainwater is naturally often not suitable for drinking, but it can be repurposed for use in non-potable applications such as toilets, washing, space cooling, cooling towers, irrigation, and some industrial applications [28,57]. Table 1 outlines various methodologies used to assess collected rainwater quality, primarily focusing on filtration [26,57,58,62,64,65,68], diversion [25,57], chlorination [26,58,64,65,68], ultra-violet lights [64], and other chemical treatments, if required [38]. Articles discussed dirt and suspended solids removal using simple and economic screens, often using sand [26,57,58,62,64,65,68] or activated carbon [68]. The quality of recovered rainwater varies with the harvesting methods, atmospheric pollution, storage methods, and the location [26,57,60,65]. Cook, et al. [60] notes that if RW collected is stored in the bedrock as groundwater and then reused, it may lead to corrosion and scaling in steel pipes, but this may be avoided by using non-metallic pipes or a water softener system. Inadequate operation and maintenance may even lead to complexities because of increased failure rates.

Bian, et al. [57] utilized solar canopy surfaces as a collector for rainfall. These surfaces have some sediments but are generally pollutant free. They discussed using slow sand filters for their efficient and economic design along with first-flush diversion. Increased turbidity of water can be avoided by using un-washed sand as the filter-material [57]. The study discussed the lower quantity of parameters such as TDS, Total suspended solids (TSS), pH levels or conductivity, Calcium hardness, and total alkalinity, indicating an increase in the number of COC, determining it fit for cooling tower applications [57]. Quon and Jiang [68], Shiguang, et al. [58], and Sousa, et al. [64] mention chlorination as a water disinfection methodology but do not discuss it in detail. Shiguang, et al. [58] used it for grey water and non-potable water for air conditioning systems as these applications have a low risk of causing viral infections amongst humans. Quon and Jiang [68] discussed that the level of water quality may depend on the system design, climate conditions, and regulation [68]. Water needs to be treated to avoid the possibility of pathogen exposure and biofilm growth in rain tanks [68]. They mentioned using activated carbon filtration followed by chlorination of the collected rainwater to improve the quality of rainwater to make it safe for non-potable applications and avoid fouling. Sousa, et al. [64] utilized the purged cooling tower water for non-potable uses after treating the purged water by filtering, disinfection by UV radiation and chlorination [64]. Rainwater was determined to be of adequate quality to produce precast concrete, cutting pieces, and for cleaning lanes in the study by Bertuzzi and Ghisi [25]. The study determined that the first flush diversion method utilized was sufficient to meet the established requirements [25]. Bertuzzi and Ghisi [25] describe that different applications for water may change the various water treatment requirements. Rainwater collected was approved under established requirements under NBR 15900[25]. After the first flush diversion, rainwater collection was free of oils and fats, water was found colorless, met solids requirements and did not present any odor concerns. The water was within pH requirements of greater than 5 pH and had zero trace of organic matter. The collected water samples were approved for chloride and sulphate levels for concrete and precast manufacturing [25]. Similarly, Thomé, et al. [26] also reported a typical rainwater pH level of around 5.5, caused due to the presence of carbon dioxide in the atmospheric water vapor, making it suitable for reuse.

Novaes and De Oliveira Cachuté [65] provided a flowchart of the proposed rainwater collection and treatment system. Rainwater would first be filtered in the pre-screening filter before entering the storage cisterns. The sand filters will remove the collected water of any sediments before treatment in the cationic exchanger and carbide removal. The stored water will be treated with limewater dosage to be used for applications such as firefighting tank water, sheeting, painting, assembly, and utilities. Stored water treated directly in the anionic exchanger can be used for painting applications at the industrial facility [65].The case study mentioned higher turbidity in rainwater due to suspended solids in the early rainfall. Thomé, et al. [26] provided a flowchart description of the rainwater treatment cycle. The water collected form the harvesting system is stored in the storage tank where it undergoes chlorination and filtered using cartridge filters before being sent to the cooling tower through a series of pumps and piping network. Water was evaluated as per the ASTM 2688 requirements, as per industrial acceptance [26]. The assessment also revealed that there was no indication of corrosion issues or fouling problems in the equipment at the facility [26,57,60,65]. James, et al. [67], Matos, et al. [62], Betz and Kuh [38], Ahmed, et al. [59], Cook, et al. [60], de Gois, et al. [61], Loper, et al. [55], and Borges, et al. [63] did not provide details on water treatment methods as part of the RWHS. Overall, the review supports the technical viability of implementing rainwater harvesting for reusing as cooling tower maker-up water and several other non-potable applications.

These results are similar to a report by PNNL, where the treatment for reuse of harvested RW is discussed to range from simple strainers to more complex chemical or mechanical processes to achieve a specific water quality. The report also mentions that common treatments may include large particle removal, filtration, and disinfection of the harvested rainwater [69] and that recommended water quality for cooling towers has the following contaminant limits: a) pH between 6 and 9, b) BOD of 30 mg/L, c) TSS of 30 mg/L, d) Fecal coliform at 200 in 100 mL of water, and e) Cl_2 of 1 mg/L[69].

3.1.1.6. Technical Feasibility Summary. Rainwater harvesting relies on collecting water, predominantly from rooftops since the water quality is much better than harvested rainwater from land catchment methods. Cisterns, tanks, and reservoirs are used in various applications to store the collected rainwater, especially in areas with limited rainfall and mismatched demand. Collection systems may require some additional modifications, including adding or adjusting gutters, piping, pumps, and valves to transport the water to and back from the storage. Filtration systems are a key component to prevent suspended impurities from getting into the cooling systems. The findings reveal that it is possible to reuse harvested rainwater as cooling tower makeup water, depending on availability (precipitation and catchment area of the roof/land). The reviewed articles reveal the possibility of increased cycles of concentration within the cooling tower and corrosion risk in carbon steel equipment, which can be avoided with proper maintenance and precaution. Treatment methods like filtration and screening are necessary to remove large debris and suspended impurities. Chlorination, UV treatment, disinfection, ionic exchange, carbide removal, limewater treatment, and activated carbon treatment can be implemented to address concerns regarding microbial and chemical contaminants. Some best practices mentioned in the review were monitoring water quality to test TDS and COC in the recirculated water.

3.1.2. Economic Feasibility

The investigation into the economic feasibility of using harvested rainwater as a substitute for current practices indicates that, while it can be economically viable under the right conditions, the economic impact varies from project to project.

3.1.2.1. Long Term Costs, Maintenance Implications, and Savings. The sixteen studies were investigated to extract discussions regarding the long-term costs and maintenance implications on using rainwater in cooling towers and any reports regarding costs versus savings. Five of the reviewed papers (Betz and Kuh [38]'Loper, et al. [55]'Cook, et al. [60]'James, et al. [67]'Ahmed, et al. [70]) did not have any discussion related to these costs at all. The rest of the reviewed papers discuss the long-term costs, maintenance, and financial implications of using RWHS directly or indirectly. The main emphasis from these studies is that even though RWHS may involve high capital costs, they provide substantial savings in the long run. Thomé, et al. [26], evaluated the use of rainwater in cooling towers and showed that even though industrial facilities have relatively low-cost water, the payback period of the investment for using harvested rainwater for the cooling towers in the petrochemical company was 24 months mainly since less maintenance treatments and operational costs were required. Additionally, they showed that energy use for harvesting rainwater, storing it and treating it returns 12,000 kWh/year of energy savings compared to the use of clarified river water which demonstrates energy cost savings in addition to direct water savings. Bian, et al. [57] in their study of the feasibility of RWH from solar panel canopies argued that the self-cleaning functionality of the technology they evaluated provided an avenue for lower maintenance costs. Along with the self-cleaning feature and the reduction in costs from freshwater consumption, this technology could have a payback period of 4-6 months as compared to other RWH technologies with expected annual savings of $25,527 to $39,027. The key factors that impact the cost of RWHS are mainly system dimensions, water demand, and water usage [61]. The size of the RWHS and the reservoir volume for storage, therefore, impact the overall costs of the system. A large roof area and bigger reservoirs will require higher costs as compared to smaller systems. In their analysis, de Gois, et al. [61] showed that having a larger system when it is not necessary increases costs without increasing any benefits. They also showed that with higher water demand for non-potable uses, the payback period of the system was shortened significantly. This is because the savings are calculated based on the amount of water purchase avoided from the municipal provider. Borges, et al. [63] reiterate the importance of these key factors and their impact on the costs of and savings from RWHS. They also find that RWH is a technically feasible and economically viable solution for large buildings given these buildings have enough rainfall, enough catchment area, optimized system design, and demand for non-potable water.

From a financial feasibility perspective, several papers examine the payback periods of the RWHS and their investment costs. Our analysis showed payback periods for RWHS to be between 0.5-10 years depending on location and other factors. Similarly, maintenance costs were determined to be between 0.5% and 1% of the installed cost. See Table 2. As mentioned previously, Thomé, et al. [26] evaluate the use of rainwater in cooling towers at a petrochemical establishment in Brazil, finding a payback period of 24 months. Bian, et al. [57] report a payback period of 4-6 months for their technology in Florida, USA. Novaes and De Oliveira Cachuté [65] conclude that using rainwater in a car making facility in Brazil results in a 9-year payback period. Similarly, Sousa, et al. [64] find a 10 year payback period for their RWHS in Portugal, while Ogwu, et al. [28] find it 1.6 years for their RWHS in Nigeria. Matos, et al. [62] evaluate the use of rainwater in commercial buildings and find that the investment costs in Portugal range between 90 to 95 million dollars with a payback period of 7 to 11 years. They highlight that this analysis did not include in their calculations the use of the rainwater in industrial processes but just in the social aspects. Finally, Bertuzzi and Ghisi [25] report that their RWHS's payback period ranges between 10.7 to 15 years with internal rate of returns 0.73%-1.07% for the precast concrete facility they study in Brazil. The papers discuss the treatment costs for filtration and maintenance being relevant aspects of the overall costs of harvesting rainwater [28,57,62]. Matos, et al. [62] state that maintenance costs are about 1% of the installation costs annually including the filtration treatment and maintaining the storage system. Similarly in their assessment of the viability of RWHS for manufacturing in regions with water stress, Ogwu, et al. [28] find that maintenance is about 0.5% of the total investment cost. Cost breakdown discussions show that the largest expenses of the RWHS are the storage tank [28,58] and installation [28,62]. The review of these papers showed that understanding the economic impacts of the RWHS for the cooling towers or for manufacturing purposes involves considering costs other than just the installation costs and maintenance costs, such as the energy costs avoided [26] due to pumping less freshwater and treating it, avoided costs from less reliance on municipal water supply [26,57,62], water and sewer tariffs [25], water savings calculated monetarily [58], the lifetime of the equipment [25], and the depreciation of the equipment [58]. Overall, the reviewed literature indicates that, although the initial costs and maintenance requirements of RWHS may be high and pose challenges for investment, the long-term benefits, such as freshwater savings, reduced energy costs, and lower treatment expenses ultimately outweigh these initial expenditures. Furthermore, while the payback period varies across different projects, the findings from the reviewed papers demonstrate that these investments are economically viable.

Table 2
Economic Feasibility Analysis of Articles in Review.

Economic Impact	Key Details	References
Initial Capital Investment	Largest expenses include storage tanks and installation costs	[28,58,62]
	Investment costs for RWHS in commercial buildings range from 90 to 95 million dollars with the payback of 7 to 11 years for a project in Portugal	[62]
Maintenance Costs	Maintenance costs are about 0.5% of total investment	[28]
	1% of installation costs annually, including filtration and storage system maintenance	[62]
	Self-cleaning features reduce maintenance	[57]
Payback Periods	Varies significantly by project: 4-6 months for a project in Florida, US	[57]
	24 months for a project using rainwater in cooling towers at a petrochemical establishment in Brazil	[26]
	1.6 years for a project in Nigeria	[28]
	9 years for using rainwater in a car making facility in Brazil	[65]
	10 years for a project in Portugal	[64]
	7-11 years for a project using rainwater in commercial buildings in Portugal	[62]
	10.7-15 years for a project at a precast concrete facility in Brazil	[25]
	20 days payback period for a project using rainwater for toilet flushing and air conditioning, or 38 days for toilet flushing alone (ignoring any maintenance costs for both) in southern Brazil	[61]
Energy Cost and Water Cost Savings	12,000 kWh/year savings from reduced pumping and treatment for a project in Brazil	[26]
	Annual savings of $26,100-$39,600 from avoided freshwater for a project in Florida, US	[57]
	Monthly savings of more than $9000 in a shopping mall in Brazil (calculated per cubic meter of water purchase avoided)	[61]
	Expected R$11,556.27 monthly savings in water (or annual R$138,675.25)	[63]
Economic Barriers and Risks	High initial investment, maintenance challenges, long payback, uncontrollable rainfall patterns	[25,26,28,57,58,62,64,65]

3.1.2.2. The Effect of Price of Water and Resource Availability On RWH. In investigating whether the price of water and resource availability affect the reuse of rainwater in the manufacturing sector, it was revealed that these are important variables for decision making. The economic feasibility of RWHS in the manufacturing sector is largely influenced by the costs of municipal water supply prices. For example, Bian, et al. [57] show that in Florida the use of rainwater for cooling tower makeup water can result in annual savings between $26,100 to $39,600 due to avoided water costs. Thomé, et al. [26] on the other hand, report that in

Brazil the investment in RWHS is more related to corporate social responsibility concerns or due to environmental policies. These show that high water costs for a manufacturing facility do make a RWHS more financially attractive. Similarly, electricity as a resource also plays a role in making RWHS attractive for manufacturing facilities. Often the use of rainwater requires less energy to pump, filter, and treat, therefore making RWHS an avenue to decrease costs. In their analysis, Novaes and De Oliveira Cachuté [65] note that electricity consumption varies depending on the volume of rainwater being moved and the pump head height indicating that higher rainwater use demands more energy. However, these increased costs still are found to be less than the energy consumed for pumping, filtering, and treating municipal water. Thomé, et al. [26] also highlight energy savings, showing a reduction of 12,000 kWh/year in energy consumption due to rainwater reuse.

Economic feasibility relies on many factors when evaluating RWHS and water availability plays a crucial role in determining whether RWHS can be viable or not. For example, in their Florida case study Bian, et al. [57] found a 24% of makeup water offset due to using harvested rainwater however, in water stressed regions' case study of Nigeria, Ogwu, et al. [28] illustrated that RWHS must be designed with the rainfall seasonality and dry months in mind to ensure that enough rainwater is stored during wet seasons that can be used during drier periods as well. Similarly, Loper, et al. [55] highlight the importance of regional water availability and its impact on the implementation of RWHS, noting that areas with seasonal rainfall can achieve significant savings by decreasing their dependence on municipal water sources during dry periods. Similarly, Borges, et al. [63] emphasize the importance of the amount of rainfall as a prerequisite for a RWHS to be effective. This review finds that even though the RWHS can be economically feasible, the high initial investment required for components such as tanks, filters, and pumps can be a financial barrier for manufacturers, and the maintenance costs can sometimes be as high as installation costs. Additionally, rainfall cannot be controlled by humans therefore, if a manufacturing facility is in a region with unreliable rainfall patterns, investing in RWHS may not be attractive. However, it may be feasible if the RWHS is designed by considering the challenges of RWH potential and large storage facilitation is included in the design to ensure continuous water supply.

3.1.2.3. Economic Feasibility Summary. In conclusion, this review finds that while the implementation of RWHS in the manufacturing sector presents financial attractiveness, their success is contingent upon a variety of factors. Table 2 summarizes the main results from the economic feasibility analysis. It highlights the key takeaways from an economic perspective that the reviewed articles covered. Economic feasibility depends on the local cost of municipal water, energy demands, and water availability, as well as the careful design of the system to accommodate regional conditions. To optimize the implementation of RWHS, manufacturers should conduct detailed feasibility studies focusing on these key variables such as local water pricing, seasonal rainfall patterns, electricity consumption, and storage capacity requirements. Specifically, they should use advanced assessment tools like Life Cycle Costing (LCC), and Techno-Economic Analysis (TEA) to evaluate system costs and expected savings. By incorporating these variables into the design and financial planning, manufacturers can ensure a more reliable and cost-effective RWH solution tailored to their specific operational and regional conditions.

3.1.3. Environmental Feasibility

Environmental feasibility for using rainwater in cooling towers discussed in the sixteen articles varied from environmental benefits to energy and sustainability impacts. Manufacturing facilities can achieve cost savings by reducing water costs [68], conserve water [26,57,58,62,65,68], reduce flood and stormwater run-off risk [62,68], reduce strain on sewage and wastewater treatment systems [59,66], reduce rainwater pollution and debris [59], and reduce surface water contamination risk [55,68].

3.1.3.1. Environmental Impacts of Using Harvested Rainwater. To have a better understanding of the environmental feasibility of using RWH for cooling tower water, the objective was to discuss the following questions in the analysis:

- What are the environmental impacts of utilizing harvested rainwater in cooling towers?
- Does water reuse or conservation impact energy consumption?
- Is there an assessment of emissions avoided through harvested rainwater use?

Human activities in commercial, industrial, and institutional buildings place significant stress on electricity and freshwater resources due to high consumption demands in dense urban development [57]. Majority of the articles discussed how the reduced freshwater consumption decreases the reliance on the groundwater resources and improves water availability [26,55,57,61–63,65,68]. Other articles provided results showing reduction in water treatment [26,68] and reduction in pollution [26,59,68] due to reduced storm water run-off [62,68] or reduced work load on the sewage systems [59] when utilizing rainwater for various applications. Matos, et al. [62] verified that harvesting rainwater helped reduce flood risk by improving the stormwater management and minimizing the ecological footprint of industrial buildings by storing collected rainwater onsite [62]. The case study, set in Portugal, also found that RWH reduced the dependence on fresh tap water and helped in mitigating water scarcity and reducing environmental impact [62]. de Gois, et al. [61] also found that reduction in wastewater discharges in natural water bodies led to reduction in sewage waste in urban environments, broadening water security and reducing stress on water supply. Additionally, water conservation can benefit the natural water resources via eutrophication and algal blooms [61]. Novaes and De Oliveira Cachuté [65] discussed how the deep lake formation used to collect rainwater for industrial and sanitary applications improves water availability by reducing total evaporation from deep lakes and minimizes the ecological footprint. Although not part of the review, the thesis article from Liu, et al. [66] and the PNNL report for the USAF from Cejudo, et al. [69] discussed the reduced flood risk and reduced loading of drainage and wastewater treatment systems, bolstering the environmental benefit argument for the reuse of rainwater for non-potable use, including cooling tower makeup water [66].

Furthermore, as per Thomé, et al. [26], use of rainwater as makeup water for the cooling towers results in reduction of approximately 24,000 m^3 of clarified water (or tap water). They also estimate the energy required for treating clarified water to be around 0.65 kWh/m^3 or 0.0184 kWh/ft^3 and that of collecting, storing, and treating rainwater to be 0.15 kWh/m^3 or 0.00425 kWh/ft^3. There is a clear reduction in the energy demands (76%) when using RWH over tap water in this case [26]. Large industrial demand helps maximize the energy and emissions reductions resulting from the collection and utilization of rainwater. Reduced energy and water consumption results in an approximately 2 ton reduction of CO_2 emissions annually, even when the primary source for the plant is hydropower with an estimated CO_2 emission of 0.17 kg/kWh [26]. No other articles discussed any significant impacts on energy consumption and reduced treatment needs associated with the reuse of rainwater in cooling towers.

The findings suggest RWH is a positive step towards promoting sustainability and ensuring water availability. Of the 16 articles that were analyzed, Ogwu, et al. [28], Shiguang, et al. [58], James, et al. [67], Sousa, et al. [64], Bertuzzi and Ghisi [25], Betz and Kuh [38], Borges, et al. [63], Cook, et al. [60] and Ahmed, et al. [59] did not provide in-depth analysis on the environmental impacts or feasibility of RWH. We suggest, therefore, that future studies not only focus on the environmental benefits of alternative sources of water but also the energy and emissions footprint of the downstream applications as well as the avoided emissions from upstream tap water resources.

3.1.3.2. Environmental Feasibility Summary. Reusing rainwater in cooling towers offers various environmental benefits, including reduction in freshwater consumption, preserving local water supply, and lower operating costs due to water savings. RW usage significantly reduces the water treatment needs, lowering the chemical and energy input. Energy for rainwater collection/treatment was found to be 0.15 kWh/m^3 vs. 0.65 kWh/m^3 for clarified water. Other environmental benefits include reduced flood, stormwater runoff risks and surface water contamination risks. Table 3 summarizes the main results from the environmental feasibility analysis. Overall, reusing harvested rainwater has an immense potential in reducing the ecological footprint associated with the industrial and commercial facilities in demand for non-potable water.

3.1.4. Policy Feasibility

This section explores the policies, regulations and standards that were discussed in the 16 reviewed articles related to the use of harvested rainwater for manufacturing processes, especially for cooling towers.

3.1.4.1. Policy Discussions and Relevance to Manufacturing Cooling Towers. Of the reviewed articles, eight covered some form of policy reporting [25,26,38,55,60,61,63,68]. The discussion of policies was broad and focused on rainwater use in general and not specifically related to the use of rainwater in cooling towers and for U.S. applications. The discussions in these articles were high level overview of the policies related to rainwater harvesting and reuse rather than policy analyses or policy guidelines. In their study, Quon and Jiang [68] explain that even though the U.S. Virgin Islands and countries such as Spain and Belgium have laws that make it mandatory for new builds to incorporate in their designs the use of rooftop RWH, the U.S. still lacks a uniform policy for RWH. Their paper shows the significance of clear policies regarding the maintenance of harvested rainwater quality and required maintenance. Similarly, Loper, et al. [55] in their study next steps mention the importance of including the state level rainwater use policies in their tool for decision makers. They state that there is no federal RWH policy in the U.S. and that RWH regulations are state-dependent and inconsistent, with some states offering incentives and incorporating RWH into plumbing codes, while others lack any specific guidelines. Cook, et al. [60] mention that building codes, industry rating schemes (Green Star, Australia; BREEAM, United Kingdom; LEED, USA), corporate policies whether mandatory or voluntary are significant motivators for using alternative water sources like rainwater. de Gois, et al. [61], similarly, highlight the trend of developing new policies and regulations that incentivize RWH and use. They mention specific countries like, Australia, Belgium, Brazil, Germany, India, Jordan, Spain, Sri Lanka and the United States.

From a manufacturing perspective, Bertuzzi and Ghisi [25] discuss standards for manufacturing concrete in Brazil that support the use of rainwater if the rainwater meets quality criteria citing Brazil's NBR 15900 standard, NBR 12655 and NBR 15577. These standards provide a framework for assessing contaminants in rainwater, ensuring its suitability for manufacturing applications, specify the levels of chlorides required in the rainwater used, and address the alkali levels in the rainwater to be used for the concrete production. Similarly, Borges, et al. [63] discuss the Brazillian Association of Technical Standards (ABNT) update in 2019 which regulates RWH and use from rooftops for non-potable uses. This shows that they have a national regulation and guidelines for the technical implementation of RWHS. Ahmed, et al. [70] mention that many states are encouraging the use of RWHS through tax incentives and rebates on rainwater harvesting equipment and highlight how these can be tax benefits for the manufacturers investing in these technologies. However, there are no specific regulations or laws identified in the text that show which states are supporting RWH initiatives. Thomé, et al. [26] point out that RWH policies should be specifically for large scale industrial uses and not just focus on its use for domestic applications. They also suggest that in addition to clear environmental RWH policies, demonstrating to stakeholders the financial benefits of RWHS in manufacturing plants is essential. These are in line with Betz and Kuh [38] suggestions for an ASHRAE standard revisions to include the adoption of rainwater in industrial cooling towers.

3.1.4.2. Policy Feasibility Analysis Summary. Significant gaps remain in policy and regulatory frameworks particularly in the U.S. in using harvested rainwater for cooling towers in the manufacturing sector. This analysis shows that there is a lack of cohesive policies that encourage and provide guidelines to use rainwater, as well as insufficient standards for treatments and quality of water. Our review of the policies identifies three categories where the regulatory gaps can be addressed to improve RWH adoption. First, we find that there is a lack of standardized regulations that help guide manufacturers in their decisions to adopting RWHS. Second, we find that incentives can be motivators for manufacturers to invest in RWH. Therefore, policy makers can explore incentives to support and encourage the use of RWH in manufacturing. And third, we find that each of the states have different sets of bureaucratic and permitting strategies which can present a barrier for investors and could be streamlined. The results highlight that there are specific regulations for using rainwater in manufacturing sectors such as Brazil's standards for the water requirements for specifically concrete production. Therefore, to address these gaps there is need for policies that promote the integration of RWH in industrial processes, including cooling towers. These policies can be guidelines and standards as well as educational policies to inform the benefits of adopting RWHS. There is also an opportunity to create specific guidelines for ensuring quality rainwater use in cooling towers as well as creating incentive-based programs for large scale industrial adoption, especially in regions with high water stress. These can be achieved by collaborations between industry leaders, government agencies and researchers to ensure a green water future. Table 4 provides a summary of the main discussed policies and standards from the policy feasibility analysis.

Table 3
Environmental Feasibility Analysis of Articles in Review.

Environmental Impact	Key Details	References
Reduced water costs	Cost savings from water supply reduction	[68]
Reduced freshwater use and increased water availability	Consistent theme; widely discussed as a key benefit; reduces reliance on groundwater and improves water availability	[26,55,57,58, 61–63,65,68]
Reduced water treatment needs	Less treatment required when using rainwater; lowers chemical and energy input	[59,66,68]
Reduced flood, stormwater runoff risk and surface water contamination	Less runoff into local waterways decreases pollutant loads	[62,68,26]
	Stormwater management improved through on-site storage, lowering flood risk and ecological footprint of industrial buildings	[62,68]
Reduced energy consumption	Energy for rainwater collection/ treatment is 0.15 kWh/m^3 vs. 0.65 kWh/m^3 for clarified water	[26]
Reduced CO_2 emissions	Estimated 2 tons/year CO_2 reduction with hydropower as the electricity source	[26]

3.2. Regional Feasibility Assessment Results

The regional feasibility analysis aims to show whether RWH and use

Table 4
Policy Feasibility Analysis of Articles in Review.

Policies/Regulations/ Standards	Key Details	References
Mandatory laws for incorporating rooftop RWH in new constructions.	Exists in U.S. Virgin Islands, Spain, and Belgium, requiring new constructions to include RWH designs	[68]
	trend of developing new policies and regulations that incentivize RWH and use in Australia, Belgium, Brazil, Germany, India, Jordan, Spain, Sri Lanka and the United States	[61]
	U.S. lacks a uniform federal policy for RWH; some states incorporating RWH into plumbing codes; regulations are state-dependent and inconsistent	[55,68]
Standards on harvested rainwater quality	Brazil's NBR 15900, NBR 12655, and NBR 15577 standards, which provide a framework for assessing contaminants in rainwater, ensuring its suitability for manufacturing applications, specify the levels of chlorides required in the rainwater used, and address the alkali levels in the rainwater to be used for the concrete production	[25]
	Brazillian Association of Technical Standards (ABNT) update in 2019 which regulates RWH and use from rooftops for non-potable uses	[63]
	Stresses the significance of clear policies to ensure rainwater quality, but no sufficient standards for rainwater treatments and quality	[68]
Suggestions on the changes to RWH related standards and regulations	Advocates for policies tailored to industrial scales not just domestic applications	[26]
	building codes, industry rating schemes (Green Star, Australia; BREEAM, United Kingdom; LEED, USA), corporate policies whether mandatory or voluntary are significant motivators for using alternative water resources such as rainwater.	[60]
	Suggests revisions to ASHRAE standards to include rainwater use in cooling towers	[38]
Incentives for incorporating RWH	Some US states offer incentives	[55]
	U.S. states are encouraging the use of RWHS through tax incentives and rebates on rainwater harvesting equipment and highlight how these can be tax benefits for the manufacturers investing in these technologies	[70]

in the U.S. industrial sector and specifically for cooling towers is feasible from policies perspective, rainwater availability standpoint, and water demand and cost perspective.

3.2.1. Regional Policy Feasibility

There are currently no federal laws or policies in the U.S. that provide guidelines related to the harvesting and use of rainwater. Each state has their own RWH policies depending on the state level needs [52,53]. Two databases provide insights into state level policies related to RWH and use: the RWH mapping tool by the Pacific Northwest National Laboratory (PNNL) [53,55], and the U.S. Environmental Protection Agency's (EPA) regulations and end-use specifications explorer (REUSExplorer) tool [52]. The RWH mapping tool by PNNL is created with the intention to provide facility managers and decision makers the information needed to determine whether for a specific location there is enough rain water harvesting potential, and whether the states regulations allow the use of rainwater [53,55]. The EPA's tool, in contrast, shows the states that allow the reuse of rainwater collected onsite for onsite non-potable use [52].

According to the PNNL data [53], the U.S. state level RWH policies can be classified into 3 categories (Figure 3). These 3 categories show that there are states that have no regulations for RWH and use, states that have state regulations, and 2 states that have very limited exemptions. The first category includes states that have no regulations for RWH, and it is not illegal to harvest rainwater and states that have no regulations but encourage RWH. These two groups within the no regulations category are states that have no bans on RWH and use. The first group in this category provides no guidelines or resources for stakeholders interested in RWH and the second group has technical standards that are state focused that encourage the use of rainwater and provide guidance. The second category defined as "states with regulations", includes states that fall into three sub-categories: those that allow RWH and use but have no specific guidelines; those with encouraging regulations that support the use and adoption of rainwater; and those with regulations that have incentives, such as state incentive programs. Finally, the "very limited" category which consists of only Colorado and Nevada. These two states highly restrict the use of rainwater, with only a few exemptions. These states have limited legal avenues for the practice, making it challenging to implement RWH on a broader scale.

On the other hand, the EPA's tool identifies 14 states with RWH policies allowing harvested rainwater use for non-potable onsite uses [52] (Figure 4). These states are: Arkansas, California, Colorado, Florida, Georgia, Hawaii, Illinois, Minnesota, North Carolina, Oklahoma, Oregon, Vermont, Virginia, and Washington. Of these 14 states, 12 (Arkansas, California, Colorado, Hawaii, Illinois, Minnesota, North Carolina, Oklahoma, Oregon, Vermont, Virginia, and Washington) fall in the "state regulations" category of PNNL, Florida falls in the "no regulations" category, and Colorado in the "limited exemptions" category. This shows a discrepancy between the PNNL and EPA data for Florida. While the PNNL data categorizes Florida as having no regulations but being a state that encourages RWH, the EPA data identifies it as a state with regulations or guidelines for RWH. The EPA data provides references to the standards in Florida that discuss rainwater harvesting (Florida Plumbing Code. 2017. Chapter 13: Non-potable Water Systems).

The non-potable applications for the 14 states identified by EPA range from using the harvested rainwater for urinal flushing, swimming pools, washing clothes, irrigation, and vehicle washing to cooling towers and industrial uses. For example, California, Georgia, and North Carolina allow a broad range of non-potable uses, including clothes washing, toilet flushing, and cooling tower makeup water, with specific requirements for filtration, disinfection, and system permits. Even though almost all these states require that the harvested rainwater be tested to meet the standards of the Clean Water Act, the permits, licensing and guidelines that each state requires vary widely. Illinois and Oregon for example, demand licensed professionals for system design and installation and others do not have this requirement. A review of these state policies found that California, Georgia, Minnesota, North Carolina, Oregon and Washington explicitly allow the use of harvested rainwater in industrial cooling towers. These states outline the necessary treatment protocols, such as filtration and disinfection, to ensure that the rainwater is suitable for cooling tower systems. However, each state's approach to permitting and regulations varies. Despite these variations, all states emphasize that the systems must meet state water quality standards and may require professional oversight for installation.

From a regional feasibility perspective, this policy investigation shows that some state level policies create barriers for interested manufacturing facilities from being able to harvest rainwater and use it in cooling towers. As water conservation becomes increasingly

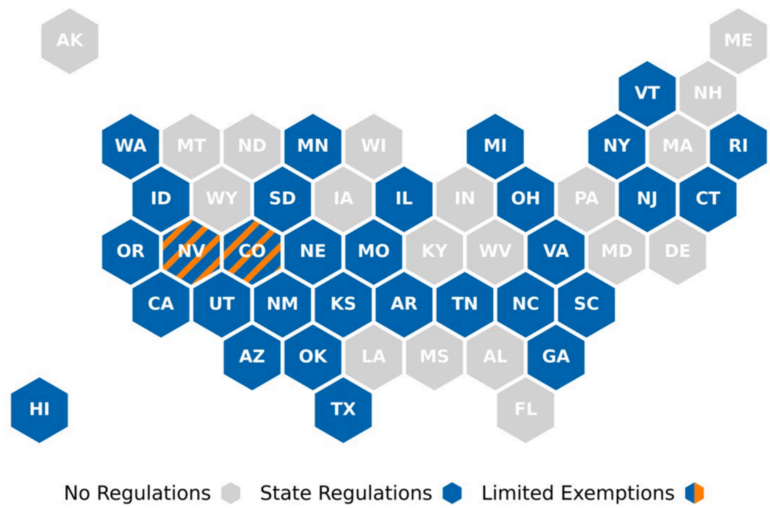

Figure 3. State RWH regulations data source: Pacific Northwest National Lab (PNNL) [53].

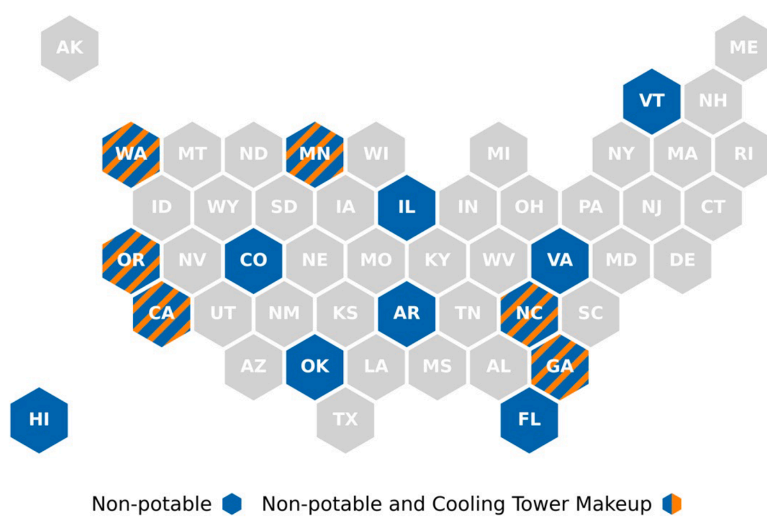

Figure 4. States that allow water reuse harvesting for onsite non-potable water uses. Data Source: U.S. Environmental Protection Agency (EPA) [52].

important, industries in these regions may look to harvest rainwater as an alternative source to reduce reliance on municipal water supplies. This is aided by 6 different states demonstrating the use of rainwater in cooling towers. However, some states actively do not allow industrial use of rainwater or may have restricted permissions for industry use due to water rights and other state specific issues. Additionally, states that are fortunate with abundant water resources may not pursue the use of harvested rainwater for manufacturing, but it could still be an avenue for these states to improve their environmental and resource management strategies.

3.2.2. Regional Rainwater Harvesting Potential and Industrial Water Demand Feasibility

After evaluating the impact of local state policies, we explored whether the RWH potential per state could meet the state's total industrial water demand. To carry out this exploration, the RWH potential data [53,55] and the industrial self-supplied water consumption data [33] were used. The data for the RWH potential metric is from the rainwater harvesting tool by PNNL which is a normalized metric representing the amount of water that can be collected and stored from rainfall in a specific region [53,55]. The industrial self-supplied water consumption data is from the U.S. Geological Survey's (USGS) dataset, "Estimated Use of Water in the United States County-Level Data for 2015."[33] This dataset provides average daily water withdrawals for various uses and defines industrial self-supplied water withdrawn as freshwater and saline water withdrawals by self-supplied industrial facilities.

The data for RWH potential (Figure 5 left map) shows that states in the Northeast, South including Hawaii, and most of the Midwest (except South Dakota, North Dakota, Michigan, Wisconsin, Minnesota, and Nebraska) have medium high to high RWH potential. This means that these states receive at least a total of 19-22 inches of rain during frost-free periods, with a potential high of 28 inches. Additionally, they have nine or more months each year with at least 1 inch of precipitation [53]. The Western states, South Dakota, North Dakota, Michigan, Wisconsin, Minnesota, and Nebraska have lower RWH potential ranging from less than a total of 8 inches during frost-free periods to 13-18 inches. This, however, does not mean that RWH is not feasible or recommended in these states, it just shows that these states have lower RWH potential. For example, Seagate, a data storage company located in Fremont California, uses RWHS to reduce their reliance on municipal water supply for their non-potable water needs including for their cooling tower makeup water [71]. Similarly, in San Francisco, the Museum of Modern Art and Market Street Place use harvested rainwater for non-potable water needs such as flushing, irrigation and cooling tower make-up [72]. It would also be interesting for facilities to explore

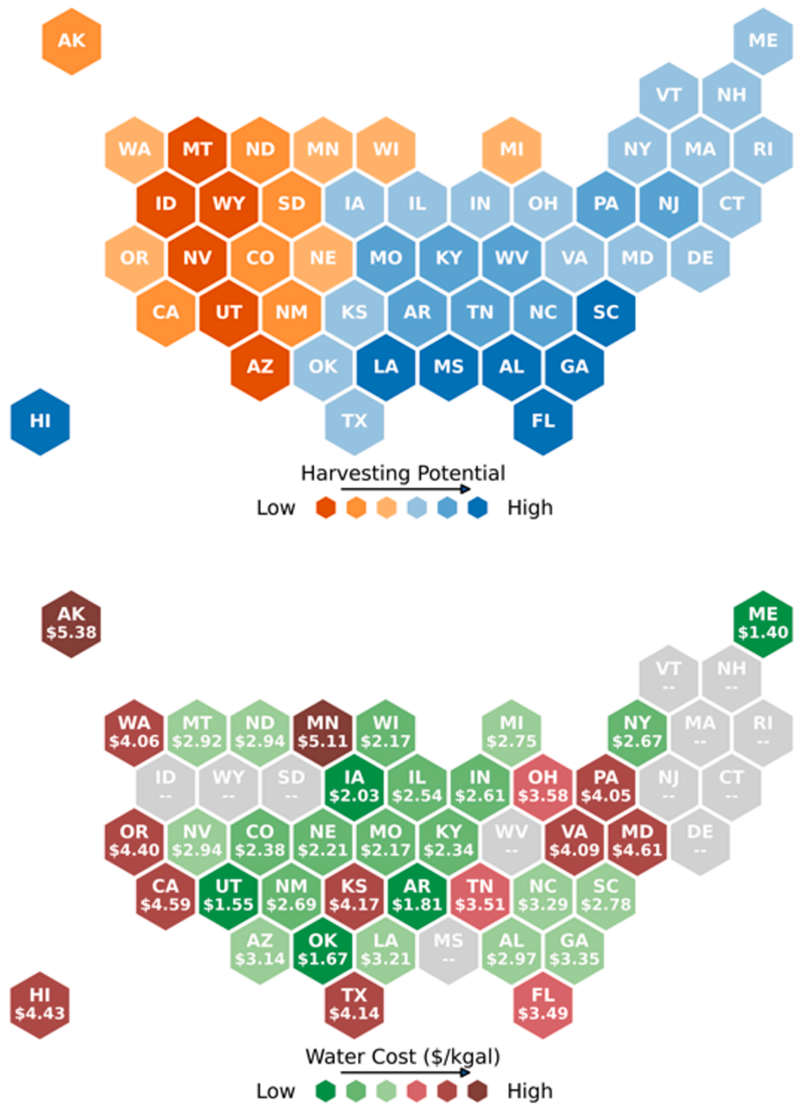

Figure 5. Top map: RWH Potential per state categorized into groups (Dark orange is the lowest potential and dark blue is the highest potential); Bottom map: The cost of municipal water for industrial use per state.

smaller-scale or hybrid RWHS in states with lower RWH potential if the harvested rainwater is not enough to meet all the water demands. Based on this data, a facility's location is a key factor in determining whether the harvested rainwater potential is enough to meet its cooling tower water demands, particularly when accounting for seasonal variations.

With that in mind, we use the industrial total self-supplied water consumption per state to evaluate if the harvested rainwater could be enough per state. If the analysis shows that the RWH potential is enough to meet the total industry consumption, then we can infer that the RWH potential is sufficient for cooling tower makeup water needs. This is because cooling tower water demands per state are a percentage of their total industry demand. To do this, state industrial land area was calculated via multiplication of US MECS 2018 industrial land area and state level industrial water consumption as a percentage of the US total (SI section 2), then the RWH potential for that area was calculated and finally, the ratio of harvested rainwater to industrial water use was calculated ($Ratio = \frac{Rainwater\ harvested\ potential\ per\ year}{Industrial\ water\ use\ per\ year}$). This is a simplistic method where a ratio larger than one shows that the harvested rainwater potential is greater than the industrial water use. The average RWH potential ratio is 2.6%, significantly below unity. On first glance, rainwater harvesting seems largely inviable; however, we know from examples previously covered that some sites are not only able to handle cooling tower makeup water loads but also other site processes like irrigation. Further study is required to provide greater granularity in data. Concrete information on industrial water usage by state and by 3D-NAICS would hone the analysis significantly. Additionally, any possibility of county level analysis would yield the strongest impact. This potential, however, is contingent on the seasonality of rain and RWH storage design. Should a cooling tower rely entirely on RWH instead of municipal water, its dependence on freshwater sources is eliminated. This transition enhances water resilience, supports zero-water initiatives, and strengthens overall water security by enabling operations to function independently of conventional freshwater supplies.

3.2.3. *Regional Water Cost Feasibility*

Lastly, we investigated the cost of water per state (Figure 5 right map) to identify from a cost perspective which states may be more inclined to pursue alternative water sources. Municipal water rates vary widely between the states. This could be due to many reasons such as water abundance, infrastructure costs, maintenance costs, source of water, ownership, and more. The map from the available data shows high costs in the west and northeast such as in Alaska, California, Oregon, and Maryland, and lower costs in the south and Midwest such as in Arkansas, Kentucky, and Missouri. The states with higher costs of water are correlated with states with lower RWH potential. This is the opposite of what is expected, as states with higher water costs would seem to be more likely to investigate sourcing their industrial non-potable water needs from alternative sources like rainwater. However, even if the RWH potential low, a facility may still be able to meet their water needs from harvested rainwater. As municipalities surge water charges due to the rising costs of water treatment and distribution, industries experience greater economic challenges. Therefore, cost-effective alternatives such as RWH will offer feasible solutions. The use of rainwater can contribute to a facility's environmental goals in addition to helping them lower water costs. While RWH may not entirely replace municipal water, especially in areas with limited rainfall, it can significantly reduce overall consumption and, in some cases, help industries become more resilient to water shortages during drought periods. Cost analyses should be conducted to compare the costs of harvested rainwater to municipal water use. Facilities that can implement RWH systems to provide rainwater more cheaply than municipal water will likely adopt them.

3.2.4. *Regional Feasibility Analysis*

The regional feasibility analysis, therefore, highlights that in the U.S. there is the potential to use rainwater for cooling towers. Figure 6 offers a comprehensive visualization of critical factors influencing the feasibility of using harvested rainwater in industrial cooling towers across the U.S. (1) RWH policies for non-potable uses per state, (2) the RWH potential per state, and (3) the municipal water costs. This first layer identifies states with supportive regulations for using rainwater for cooling towers and those with no regulations. The second layer highlights the states that have the lowest RWH potential to the highest, identifying directly the availability of rainwater for harvesting. The last layer showcases the cost of municipal water rates per state, a variable that may be influential in pushing industries to look into harvested rainwater as an alternative water source [70]. Together, these three layers provide a powerful tool for assessing regional viability and guiding industries in making informed decisions about RWH as an option for them.

The systematic literature review and regional feasibility analysis demonstrate that using RWH for cooling towers is regionally possible, technically feasible, economically viable, and environmentally beneficial. However, further research is necessary to examine the life cycle environmental and cost impacts of RWHS. Additionally, the potential for widespread adoption is supported by encouraging state policies, regional RWH potential, and the growing challenges of water costs across the U.S. The review results show that the most studied technology in the published literature is rooftop RWH. The review also shows that while adopting RWH requires some changes to infrastructure and the implementation of filtration techniques, rainwater can ultimately be used for cooling towers. The systematic literature review revealed that the initial investment costs of RWHS may be challenging but eventually they have negligible operations and maintenance costs, and while the payback periods may vary, the systems are economically feasible. Additionally, the findings from the review discovered that water costs are indeed an important factor in facilities decision to invest in alternative water resources. Therefore, when coupled with the results of the regional feasibility analysis, the outcome is that regions with higher water costs are more likely to benefit from adopting RWH for cooling towers, particularly where policies support its implementation and where RWH potential aligns with industrial needs. Industries in states with supportive policies should be encouraged to implement RWH as a reliable alternative for cooling tower water needs. This study shows that policy makers in states with restrictive policies should explore reforming their policies to create a legal framework supporting industrial rainwater use if possible, depending on water rights and other regulatory standards related to rainfall in their states.

4. Study Limitations and Future Work

While the study provides valuable insights into the potential for using harvested rainwater in industrial cooling towers, there are several limitations to consider in the analysis. Acknowledging these limitations will help contextualize the findings and guide future research. First, for the systematic literature review, the included articles in the study were dependent on the keywords and search strings used, the databases investigated, as well as the inclusion exclusion criteria. These provide opportunities for future systematic review studies to build on this paper by expanding these criteria to include other publications that may have been excluded from the current study and help enrich the analysis results. The inclusion of non-peer reviewed publications such as industry reports, and magazine articles which were out of the scope of this study may also help in our understanding of the use of rainwater in cooling towers. Finally, for the regional feasibility analysis, this study focused on state level analysis. Future studies can expand this study to more granular levels to include local variations in precipitation patterns, microclimates, and regional disparities within states. The analysis of water costs assumed uniform pricing structures across industries, which may not account for variations in water tariffs or discounts offered to specific sectors. Moreover, the estimation of industrial water demand does not account for sector-specific differences in water usage, potentially affecting the applicability of RWH solutions. Future studies can investigate the infrastructure required for implementing RWHS, and challenges such as storage, filtration, chemical treatment, and distribution which may limit feasibility in some regions. Finally, while the analysis considers the economic aspects of RWH, it does not fully explore non-economic factors like public perception or corporate sustainability goals, which may influence decision-making. These are all opportunities for future studies to better understand the feasibility of RWH for cooling

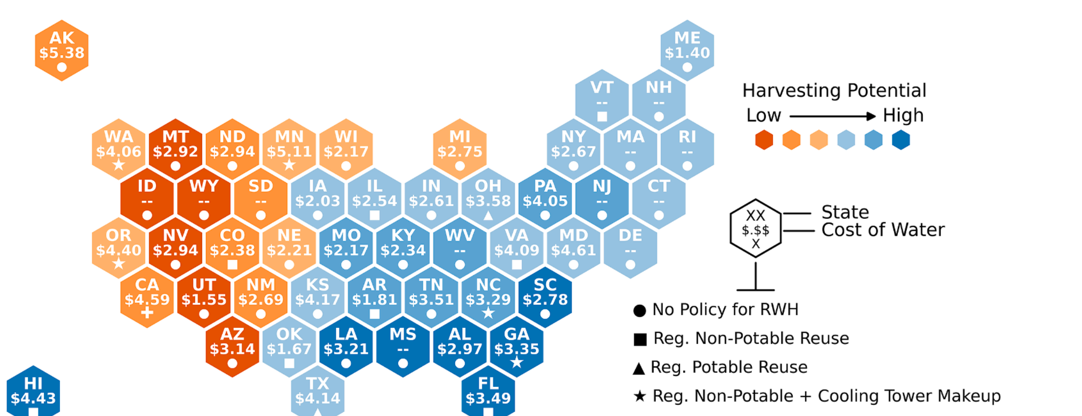

Figure 6. Multilayered map showing the RWH potential, water costs, and state policies in the U.S.

towers. These limitations suggest that while the findings provide valuable insights, this study is a preliminary step in advancing our understanding of RWH for cooling towers, and further research is necessary to deepen our insights and address the complexities associated with its implementation.

5. Conclusions

This study investigated the use of harvested rainwater for cooling towers through a comprehensive systematic review and a regional feasibility analysis of integrating RWH in U.S. manufacturing cooling towers. The results revealed that utilizing RWH for cooling towers is both technically achievable and economically possible, with positive environmental impacts. The potential for broader adoption is strengthened by favorable state policies. The results show that rooftop RWH is the most frequently studied method. While implementing RWH requires infrastructure modifications and the incorporation of filtration systems, rainwater can effectively be used for cooling towers. The main challenge with rainwater use is its seasonal variability and dependence on climate conditions. Overestimating rainfall availability can lead to the need for large storage capacities, which significantly increase system costs, as reservoirs are the most expensive component. However, large industrial facilities, with their high-water demand and extensive surface areas, can improve rainwater collection efficiency. This analysis showed that regions with higher water costs are more likely to benefit from RWH adoption, especially where supportive policies are in place and the regional RWH potential aligns with industrial needs. The study provides a solid foundation for understanding the potential for using RWH in industrial cooling towers.

CRediT authorship contribution statement

Aline Banboukian: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Indraneel Bhandari:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Wei Guo:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition, Conceptualization. **Christopher Price:** Visualization, Writing – review & editing. **Miles Nevills:** Formal analysis, Methodology, Validation, Writing – review & editing. **Ahmad I. Abbas:** Writing – review & editing, Validation, Methodology, Conceptualization. **Thomas Wenning:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rineng.2025.107489.

Data availability

Data will be made available on request.

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