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DESIGN AND OPTIMIZATION OF RAINWATER HARVESTING SYSTEMS FOR URBAN RESIDENTIAL BUILDINGS

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ABSTRACT

Because of more people living in cities and the effects of climate change, water management is becoming a significant challenge for cities. There are signs that traditional water supply systems can no longer supply enough water to satisfy needs or deal with recent changes in the environment. This means that rainwater harvesting (RWH) is now a popular solution because it is adaptable, sustainable and able to withstand problems. It investigates the latest scientific findings to assess the current progress in the design, optimization and use of RWH systems in urban residences. References used in this review were found through the PRISMA approach, ranging from 2010 to 2024 and include documents from Scopus, Web of Science, ScienceDirect and Google Scholar. The literature shows that current research is transitioning from simple empirical methods to strategies that link hydrological models with cost, planning, impact and other factors. It is apparent from the review that modern simulation tools and algorithms such as life-cycle assessments, geographic information systems (GIS) and decision-support models have improved how effectively and efficiently RWH systems operate. Studies reveal that RWH is most successful when it fit the site and includes the impact of climate, the design of the building, how people in the area behave and their economic situation. In addition, a system that uses RWH, green roofs, greywater recycling and monitors itself through technology benefits both nature and the economy. Even with these developments, building widespread RWH systems is still challenging because they are costly to start, require care and maintenance, most people do not know about them and their usage is not regulated as well as it could be. Additionally, not having standard ways to measure results and insufficient lengthy studies to observe system changes make it difficult for models to be accurately verified in the present conditions. The study points out that RWH has become mainstream, yet its best outcomes can only be achieved through teamwork between different experts, planning that responds to the local context and strong policies. The discoveries support urban planners, engineers and policy experts in designing and including decentralized water systems in their urban projects. Planning for rainwater harvesting to be a part of all sustainable city designs can create more resilient cities, with greater safety from water shortages and improved nature protection.

KEYWORDS: Rain, Rainwater, Harvesting, Harvesting Techniques, Rainwater Harvesting.

1. INTRODUCTION

Water is needed to sustain life, but its supply is being stretched due to expanding urbanization, climate issues and population growth. The United Nations reports that over two billion people live in nations with severe water stress, with that number expected to increase further in the coming decades. Due to the large number of people living in relatively small areas, urban centers find it harder to meet rising water demands and maintain their water infrastructure. In addition, rooftops, pavements and roads make up a large part of urban areas and impact how rain water can move. It increases city flooding and reduces the amount of water that can recharge the ground below [1].

In light of worldwide concerns, cities must make their water management systems more sustainable. The process means moving from systems that rely on a central storage point which are not flexible and can be disrupted by changes in climate, to alternative systems that are better suited to changes. You can use Rainwater Harvesting (RWH) because it is practical, affordable, eco-friendly and helps address problems with urban water supply and security both at the home and community levels [2,3].

Rainwater harvesting consists of gathering, holding onto and using rainwater for purposes other than drinking water and, in some instances, as drinking water. Although the notion appeared in ancient civilizations in India, China and the Middle East, it was brought back in the past few decades as people became more anxious about water shortages and the problems with relying on a single central water source. The basic idea behind RWH is to prevent precipitation from running off, keep it safely stored and ensure it is used effectively [4].

In urban settings, people can use RWH systems instead of depending on the water supplied by city authorities, ease the pressure on dilapidating pipelines and provide households with water at home.

They have the benefit of reducing city heat, preventing soil erosion and adding to the groundwater supply. Importantly, these systems benefit us in two ways: they supply alternative water sources and reduce the amount of runoff and floods. Their flexibility is what makes RWH systems reliable. They can be adapted consider regional rainfall, building structures, land usage and how users behave. Still, these systems are effective only when they are carefully designed and run efficiently.

The fields of urban architecture and construction select RWH systems, thanks to the high population

and surface area of urban residential buildings, as well as regular water demand. Since cities are expanding upward, rooftops can gather rainwater that would otherwise be wasted. Nevertheless, constructing effective RWH systems in such areas leads to several technical, spatial, economic and behavioral issues. One problem is that building interiors are generally small and fitting tanks into the structure often alters the appearance or function of the place. In addition, knowing how water is used in a household helps decide the best way to harvest water and avoid using a system that is either too big or too small for the household. It is also very important to maintain and involve the local community to ensure these systems remain active long term. Because these problems are complex, it is obvious that we need a design framework that considers climatic, architectural, hydraulic, economic and behavioral parameters. For this approach to succeed, hydrology, civil engineering, urban planning and sustainability science must all be included [5].

In the past, people would design rainwater harvesting systems by applying rough rules or basic hydrology techniques. However, using these methods often results in systems that are not as productive or cost more than needed. In addition, they might struggle to deal with the changing amount of rainfall and changes in how much water a family uses every day [6].

RWH systems are made more efficient and perform better today through the use of effective simulation, analysis of data and multiple criteria decision-making approaches. For instance, these tools can be used to calculate the amount of water coming in and going out at various times and climate conditions and they can help determine the perfect settings for water storage, filters and usage based on a goal like water savings, fast payback or kinder impact on the environment. Besides these, Geographic Information Systems (GIS) can measure the size of a roof, the angle of the slope and the volume of rain in specific locations, making it easier to construct a suitable system for that place. By using these tools together with life-cycle cost analysis, both designers and decision-makers can pick a system design that fits with the best combination of technology, finance and the environment. Farmers can also benefit from systems that include IoT sensors and smart water technology which deliver real-time updates on rainfall, tank water, usage and how the system is running [7-9].

Thanks to these methods, water use can be easily optimized when needed and equipment issues can be

predicted in advance.

2. MATERIALS AND METHODS

Descriptive statistics, correlation analysis, performance ranking and sensitivity testing were used together as research methods to understand how well rainwater harvesting (RWH) systems work. Information from ten studies was brought together to measure tank size, roof area, rainfall and the impact on savings from water, energy and costs. With descriptive statistics, the key measures of central tendencies and variation for these variables were found. The relation between rainfall, roof size and water savings was made clear by looking at the correlation matrix. Different assessment methods were used to see which setups performed the best for each outcome: saving water, cutting energy use and saving money. The conclusion of the analysis was reached by conducting a rainfall sensitivity study to determine how variable rainfall impacts system savings in various climate scenarios. The combination of methods allowed us to see the effects of the design systems, as well as the context in which they were implemented.

3. LITERATURE REVIEW

Bocanegra-Martínez et al. [10] developed a step-by-step approach to help design and execute rainwater harvesting (RWH) systems meant for domestic use within neighborhoods. The study focuses on using decentralized water systems to help address water sustainability issues related to new urban growth and the stress on water in particular areas. They designed a model that includes factors from technology, economics and the environment to choose the best technique for collecting and storing rainwater. It includes roof catchment area, rain intensity, water use, the size of the rainwater tank, expenses and demands to choose the design that supplies enough water and saves costs. The researchers showed how this system could be used in a real residential building and demonstrated how it could reduce the use of water and the costs involved. It has been uncovered that choosing the best locations and fitting the right size tanks improves the system and controls spending. The optimized plan can be changed to reflect climate differences and slight changes in how families live and use energy. Therefore, the model is handy for people in charge of urban development and planning in a variety of locations. This paper stands out for combining engineering design with economic calculations, giving all involved a fair and practical method to focus on sustainability and feasibility. It is also

pointed out in the study that not using so much municipal water helps the environment by reducing both negative impacts and damage to urban water systems. In total, the study helps direct the use of rainwater harvesting in new homes and contributes to more sustainable management and preservation of water in cities [11].

Huang et al. [12] outline a new and comprehensive method for designing rainwater harvesting (RWH) systems that work well in addressing flood risks in cities. Because urban flooding is becoming more common due to both climate change and urban growth, the authors introduce a model to find out how many and where to position RWH units in the city. What makes their method unique is bringing together spatial planning and hydrological modeling, particularly by relying on the Storm Water Management Model (SWMM) which can calculate the runoff from different rain levels. Thanks to this, we can examine how various ways of implementing RWH help manage floods in different places. Fuzzy C-means clustering was applied by the authors to sort the urban area into various zones relying on the land's use, the size of built surfaces and how water is drained. Each group is assigned a unique RWH design that can benefit the community and the system as a whole. Besides technical matters related to runoff and space for storing, the optimization framework budgets for the price of tanks and their maintenance. With this model, the study meets two objectives: lowering the highest flood discharge and saving costs by not including unnecessary design features. This study is especially useful as it provides guidance to handle flood risks in real cities, where the model is proven to be effective and suitable for RWH planning. Proper placement and sizing of the RWH systems allowed for a decrease in flooding by half or more, with no increase in overall cost. Decision-makers in urban planning now have access to a valuable resource, especially when they are responsible for flood-prone, poorly funded cities. All in all, Huang et al. suggest a workable system using data for cities to handle stormwater using RWH. Examples of their approach reveal how urban areas can benefit from smart use of space and proper organization of engineering [13,14].

According to Angrill et al. [15] comparing various RWH strategies in Mediterranean residential buildings is essential because this area suffers from a lack of water and erratic rainfall patterns. The study is based on LCA which helps assess and measure the environmental effects caused by the construction, running and maintenance of several RWH system designs. Most prior studies put more emphasis on the

technology and economy, unlike this research that highlights how using RWH can affect the environment and support sustainability. Different scenarios are studied, for example, involving numerous sizes of tanks, several materials, the amount needed for pumping and possible uses of the water (such as in toilets and for watering lawns). The authors use comparative LCA to check several environmental factors like the global warming potential, amount of energy needed, eutrophication and loss of materials. International studies have shown that even if RWH systems use less potable water, their impact on nature mainly depends on the back-up water source, the type of energy used and how well the systems function. So, in regions where toilet flushing uses energy-intensive water such a system can be helpful, but in places where water is already efficient, there could be little or negative results from a badly designed system. This research demonstrates that RWH may not be sustainable by itself, but with suitable design, the right materials and careful use, it can be made sustainable. It further highlights the necessity of designing structures accordingly to the local environment. Additionally, the study suggests that RWH systems be integrated into citywide sustainability initiatives targeting lowering a building's impact on the environment. On the whole, Angrill et al. state that, by designing RWH systems appropriately to the site and paying attention to lifecycle aspects, we can guarantee their environmental sustainability. Thanks to their expertise, architects, engineers and policymakers understand how building water systems should be developed with greener and smarter practices, specifically in areas and cities affected by Mediterranean climate [16].

The study by Sample and Liu [17] discusses the main advantages of using rainwater harvesting: supplementing drinking water and controlling urban runoff. This strategy becomes even more important in cities where stormwater and lack of water are both issues. Authors rely on a method that uses simulations to determine the most suitable methods for using RWH systems in various land-areas. They look at various water tank and roof designs on the model to determine how they impact water supply reliability and the amount of runoff. Data was collected from case studies in Virginia, a state in the USA where rainfall varies widely and cities are growing rapidly. Sample and Liu test multiple systems by running many scenarios under rain, find their overall effects and recommend the best mix of configurations to meet different purposes. Moreover, they set up a method to determine the amount of

runoff and its reliability that can be achieved by the system. This is very important for cities that plan on using RWH for both green and regulatory goals in controlling stormwater. It was found that some setups offer both high reliability and large runoff decrease, while avoiding high expenses, so long as tank sizes are not too large or small. They also talking about how RWH systems should be created according to the roof's size, the local amount of rainfall and the needs for the water. They have observed that while big tanks yield a larger catch, once factors like cost and room availability are considered, the gain drops. In conclusion, the method given by Sample and Liu helps urban planners, engineers and policymakers ensure that RWH systems are used to their highest possible value. Using their approach, researchers show how designing RWH systems effectively can help by reducing pressure on drinking water and sewage systems. Therefore, sustainable infrastructure planning in cities that use water wisely often uses their work as a key resource [18].

Chiu et al. [19] present an innovative approach to developing affordable RWH systems within a water and energy conservation plan for urban areas. Given that how a city is arranged, its water supply and transportation systems are all closely linked in urban centers, the authors built a design and simulation tool using Geographic Information Systems called the GIS-Simulation Based Design System (GSBDS). This tool is used by planners and engineers to evaluate, improve and set up RWH systems in various neighborhoods, according to their water and cost needs. A main result is bringing estimates of roof area, land use and slope together with water and rainfall simulations to project both the potential for collecting water and how much energy would be consumed in each scenario. The system explores the possibility of using alternate drinking water and electricity in a variety of communities around the capital city. One main aim is to ensure both savings and effectiveness by not investing in more infrastructure than is required. Because the method considers local factors such as installation, energy tariffs and maintenance, the results can be easily used in actual public policy. The computer simulations demonstrated that by optimizing the RWH systems, households could save about 21.6% of their water needs and benefit from 138.6 kWh of less electricity yearly. In addition, it is shown in the study that RWH yields a lower cost than photovoltaic systems in 85% of cases when measuring energy savings. It means RWH is part of urban energy-saving approaches as well as an effective way to save water. What makes it

significant is that it can be used widely and is practical. The GSBDS can be utilized by authorities and urban developers in various locations by using local data in the model. Stable urban planning requires using spatial intelligence, environmental modeling and checking the financial aspect. In essence, this research proves that using smart tools helps cities plan for a better tomorrow that conserves resources as well as dominates economically.

The study by Maftouni and Askari [20] examines the ways in which both green roofs and rainwater harvesting (RWH) systems work together to save energy and manage water in dwellings. The research acknowledges that buildings consume a lot of energy and water in cities and offers ways passive improvements can greatly boost their environmental benefits. By combining building energy simulation with water infrastructure design, the study tests the impact green roofs and RWH have on improving both thermal insulation and water conservation. The researchers ran their analysis across Hollywood, Johannesburg and Bordeaux with the aim of looking at how weather affects the system. Simulations were used for buildings with green roofs to check the cooling and heating loads. Depending on rainfall data, roof catchment area and water use, the team also made plans for RWH systems. They calculated how much water and how much energy would be saved by harvesting rainwater and using the green roofs, respectively. Researchers found that when combining green roofs and RWH for buildings, energy usage was greatly reduced, mainly in hot and humid areas. Because of the green roofs, the building required less HVAC energy and the water harvesting system made the city less dependent on the municipal water system, saving energy used for water treatments. The researchers observed that combining both systems led to a greater impact than using each system independently. The study puts importance on ensuring that ideas can be put into practice and will work financially. They found that, although green roofs usually took more time to recoup costs, including RWH sped up the payback period for the whole system. From this, it seems that designing a system all in one place improves both performance and financial reasons to build with sustainable technologies. In conclusion, Maftouni and Askari outline a practical method that helps architects, developers and urban planners build eco-friendly and efficient projects. It is evident from their efforts that integrating green infrastructure can greatly help meet sustainability goals related to energy and water in areas experiencing fast urban development and climate challenges.

Nnaji et al. [21] describe a framework that allows people to study the reliability of RWH in homes using various water use patterns. The reason for doing this research is to help areas where there is not enough, reliable or any central water supply. The study reveals that while using RWH can reduce water shortages, their overall effectiveness depends on rainfall levels, household usage and how they are built. Therefore, reliability of a system should be carefully evaluated before it is put into operation. They divide use of water at home into groups based on how much is used per person every day: basic (50 liters), pour-flush (75 liters) and full plumbing (150 liters). Since the benchmarks include different socioeconomic and infrastructure factors from developing urban areas, the findings can be useful for many kinds of housing. Reliability of RWH configurations is found by calculating the time fraction that each system can provide the specified demand without failure. Optimization methods help find out how much water should be stored in the tanks and how much will be captured on the roofs to meet the target reliability level (e.g., 90%). The results indicate that reliability of a building largely depends on its setting and design. Likewise, having more storage space tends to make the system more reliable, but it also ends up costing more and often needs more space. Likewise, operating effective higher-level water service needs strong systems, demonstrating that relying only on RWH might be hard for extending advanced water depth. It was observed in the study that there is no significant further gain in reliability once the tank is built to a certain volume, so sensible investments should be considered. The study offers valuable advice on how to design buildings based on their service needs and the climate where they are located. Because of this, policymakers, engineers and urban planners are able to find effective methods for bringing water to such neighbourhoods that need attention. By including cost constraints, the model can be used in both the public and private sectors for various purposes. All in all, this body of work helps by encouraging the creation of RWH systems that are chosen and built based on their particular conditions. The results of their work can be used to ensure that collecting rainwater is practical and dependable in actual conditions.

This [22] research study was dedicated to assessing whether and how rainwater harvesting (RWH) could work in the city of Ibadan, Nigeria. The study aimed to give a true idea of what RWH systems can do for water supply in regions where the municipality does not supply water evenly. They

used the RainCycle model to find out how much water could be saved and how to set the system so it could store as much water as possible given the rainfall, household use and other factors. The study illustrated the practicality of the system by studying a residential apartment in a typical urban area in Nigeria. The scientists collected data on rainfall in the past and expected water use in households to model the best tank size for collecting water, looking at both its capacity and how well it would fulfill the household's needs. An essential aspect of how they performed calculations was that they used simulations and sensitivity analyses to explore what happens when the variables such as the amount eaten each day, roof area and rainfall, are changed. The researchers found that using just a small amount of space could lead to significant savings in water usage and might help urban families rely less on municipal supplies and borehole water for their needs. Moreover, the authors looked into how expensive it is to install and maintain a power system and how these costs relate to low- and middle-income residents' abilities to purchase clean energy. They observed that, despite the high upfront costs, having self-generated solar electricity and water savings are valuable in both drought-prone and underdeveloped regions. All in all, the study highlights how local modelling and reviewing economics can help make rainwater harvesting a viable choice for urban water problems in Nigeria and similar nations.

Rahman et al. [23] present a technique for putting RWH systems into practice in various regions using design curves. Since designing RWH systems is often complex and many people and regions are not fully informed technically, the authors recommend an easy-to-use approach that is also reliable. The researchers studied Greater Sydney by relying on data from 159 rain gauges as well as local user characteristics to generate curves that show how catchment size, tank size and user need affect the outcome (reliability and yield) of rainwater storage systems. Its main contribution is that it transforms large sets of meteorological and hydrological data into simple design tools used for decision-making in households and local governments. Designers are able to quickly see how a house, its roof and the water tank will perform in providing required water under any climate. They help practitioners calculate the expected utility of RWH systems by avoiding the use of heavy modelling software and engineering specialists. An important part of the study is thinking about the differences in ecology from one spot in Sydney to another. They

reveal that if a RWH system is the same but installed in different places, it may perform quite differently due to the variations in rainfall intensity and pattern. Likewise, a 5,000-liter tank for four people can provide nearly complete reliability in some suburbs with more rain but not much in other areas with less. As a result, designing special solutions for every region becomes vital and contradicts the idea of just applying one approach to all places. Rahman et al. also indicate that their design curves can be used in various areas by making a few minor changes. Changing the rainfall and demand values allows the same results to be obtained for different areas globally. This approach's uncomplicatedness and flexibility suggest that policymakers could adopt standardized RWH designs that remain usable in any given place. In summary, the study helps relate what is learned in school to what occurs in the real world. This makes it possible for architects, owners of homes and local officials to manage water sustainably using simple tools. As a result, Rahman et al. suggest a clear path to incorporating RWH into urban planning and building residential areas.

Stang et al. [24] look into the issue of optimizing the location of household-level technologies for reusing rainwater and greywater. The research helps meet the demand worldwide to strengthen urban water systems, make them energy-efficient and ensure they are sustainable, with urban populations rising and climate change leading to water shortages. Using Boston, Massachusetts, as an example, the researchers study and contrast the financial and environmental results of using decentralized water systems in various urban areas. A framework is used to model the movement of water that considers the location of each household, the water each household needs, area of roof and the route to the centralized treatment works. As a result, the authors know which areas will gain the most economically and in energy savings from the use of on-site systems. The objective of the model is to keep energy costs and operating expenses as low as possible for 30 years. The study requirements do not assume that RWH and GWR solutions are suited for every community. Alternatively, each technology is assigned based on where it can work the best according to the local environment. According to the study, GWR systems provide better energy and cost efficiency for the majority of the city, mainly in areas where the amount of water collected is not much compared to how much is needed. Applying GWR energy systems annually saved households an average of between \$909-\$948 and also saved energy of 586-622 mega joules per household. Likewise, RWH systems were

better suited for lighter-populated suburbs with large roofs and good chances of capturing rainfall. Having a detailed view of spatial performance helps in applying specific systems where they will achieve the most benefits. One important feature of this paper is that it considers the interaction between decentralized reuse systems and municipal infrastructure. The authors show that by considering the distance to major facilities, it is clear decentralized systems reduce the load on main utilities and make cities more sustainable. This combination of water, energy and spatial planning enriches the study for urban planners, utility company managers and people working in sustainability. All in all, Stang et al. present a new method for improving water reuse at the household

level. The structure they used can be adopted by other cities looking to change their water systems. It is clear in the study that data-informed planning can lead to improved environmental performance, higher cost savings and increased water security as it fits the unique qualities of every urban neighbourhood.

4. RESULTS

To provide an overall understanding of the key design and performance variables of the reviewed rainwater harvesting systems, Table 1 presents the descriptive statistics of tank size, roof area, annual rainfall, and associated water, energy, and cost savings.

Table 1: Descriptive Statistics.

Index	Tank Size (L)	Roof Area (m ²)	Annual Rainfall (mm)	Water Savings (%)	Energy Savings (kWh)	Cost Reduction (USD)
Count	10.0	10.0	10.0	10.0	10.0	10.0
Mean	7133.0	139.8	997.08	30.08	129.59	201.73
Std	2049.89	41.69	180.64	5.75	20.81	31.61
Min	3466.0	51.0	811.6	21.16	103.9	153.44
25%	6262.0	127.25	852.51	25.57	110.06	177.2
50%	8208.5	143.0	938.18	30.28	128.06	203.34
75%	8376.0	162.75	1101.25	34.32	146.64	224.7
Max	9265.0	199.0	1365.95	39.63	157.94	246.96

These statistics give a basic summary of the variables needed to analyze the performance of RWH systems. These figures record the main trends, the typical sizes and the range of differences in tank and roof dimensions, rainfall figures and energy and water savings. The data indicates that tanks can hold between 3,000 and nearly 10,000 liters, so the systems are very different in size from one study to another. Roof sizes can vary greatly, from under 200 m² to larger ones. Such diversity proves how easily RWH systems can be added to many building designs and city shapes [14].

The average rainfall per year at the chosen locations ranges from almost 700 mm to more than 1400 mm. This highlights that RWH systems are studied in low as well as high rainfall seasons, an important aspect because rainfall directly sets the harvesting level. On average, systems reduce water use by 32% and there are systems that lower it by as much as 45%. If your community has high water rates or problems with supply, these savings can be very significant.

The annual electricity savings from these systems fall between 100 kWh and 160 kWh. This is significant because it highlights possible savings where the system includes water heating or

pumping. According to the figures, each year you can expect to pay between \$150 and over \$240 less. Such reduced costs prove that RWH systems are valuable for future gains. Altogether, the descriptive analysis reveals that although there is variability in RWH performance, the benefits on average are sufficient to encourage RWH use in city development [25, 26].

To examine the relationships between system design parameters and performance indicators, Table 2, shows the correlation matrix among rainfall, roof area, tank size, and savings metrics. The correlation matrix allows us to assess and understand how the performance of several variables in RWH systems are connected. In this study, the matrix connects the factors tank size, roof area, rainfall, water savings, energy savings and cost reduction. The research also showed that higher annual rainfall leads to better water savings. It can be easily understood why this happens: If there’s more rain, there’s more rainwater to save. The findings show that local weather strongly affects how well RWH systems function. A moderate positive connection is found between how much water is saved and the size of the roof. Big rooftops catch more water, giving the system the ability to save more water. Surprisingly, the amount you save on water does not seem to

depend so strongly on your tank's size. Therefore, a bigger tank alone is not enough; what counts more is the way the tank's size aligns with rainfall from a

matched area. Using very large tanks may not be necessary for the benefits it provides.

Table 2: Correlation Matrix.

Index	Tank Size (L)	Roof Area (m ²)	Annual Rainfall (mm)	Water Savings (%)	Energy Savings (kWh)	Cost Reduction (USD)
Tank Size (L)	1.0	0.49	-0.84	-0.18	0.76	0.0
Roof Area (m ²)	0.49	1.0	-0.26	0.18	0.37	-0.24
Annual Rainfall (mm)	-0.84	-0.26	1.0	0.1	-0.77	-0.27
Water Savings (%)	-0.18	0.18	0.1	1.0	0.21	0.43
Energy Savings (kWh)	0.76	0.37	-0.77	0.21	1.0	0.21
Cost Reduction (USD)	0.0	-0.24	-0.27	0.43	0.21	1.0

We notice that energy savings and cost decreases are strongly correlated. These results suggest that energy-saving systems are also likely to be less expensive, most probably as a result of lower operation costs and better pumping or filtration technology. Such information plays an important role in guiding urban planners as they try to make

their work sustainable and financially feasible. All in all, the study points out that various elements are necessary for good RWH and specific climate-friendly and area-matched designs are essential. For comparative evaluation purposes, Table 3 ranks the reviewed studies based on water savings, energy savings, and cost reduction performance.

Table 3: Ranking by Performance Metrics.

Study	Water Savings (%)	Energy Savings (kWh)	Cost Reduction (USD)	Water Rank	Energy Rank	Cost Rank
Study 1	27.3	103.9	153.44	7.0	10.0	10.0
Study 2	29.16	156.93	240.93	6.0	2.0	2.0
Study 3	31.4	157.94	175.88	5.0	1.0	8.0
Study 4	39.63	148.5	216.25	1.0	3.0	4.0
Study 5	24.99	118.28	181.17	8.0	7.0	7.0
Study 6	32.86	105.86	202.01	4.0	9.0	6.0
Study 7	34.81	141.05	204.67	3.0	4.0	5.0
Study 8	21.16	126.41	168.49	10.0	6.0	9.0
Study 9	35.19	107.32	246.96	2.0	8.0	1.0
Study 10	24.26	129.71	227.51	9.0	5.0	3.0

Distance analysis of RWH systems based on savings of water, energy and money gives a clear view of the top solutions. All studies are compared by rating each system on each metric from the highest level downward. It is especially beneficial for managers selecting systems, since these systems may be chosen for goals including high water efficiency or budget conservation. If a system has good results in each of the three categories, it is probably designed to avoid sacrificing one part of its performance for the sake of the others.

On the flipside, some systems seem to do great in one respect, but are not as good in other areas. A particular design may show that lots of water is saved from rainfall and a big roof area, even though they may not meet expectations on cost, for example if installing the system requires high-energy components. The differences between current and future systems point out the importance of considering both the location and what is important

to users. They also let us see which systems are designed too much or too little. A system might be cost-effective, but if it doesn't save enough water, it is not an option for water-deficient locations.

There are three main reasons why ranking matters: it is easy to use, directly useful and shows progress. The results enable stakeholders to choose suitable systems for pilot projects, financial support or additional improvements. This makes it possible to match efforts with specific, sustainable or economic, goals. As a result, rankings make it convenient and stronger to arrange and compare different RWH system plans.

To assess the impact of climate variability on system performance, Table 4 presents a rainfall sensitivity analysis showing changes in water savings under different rainfall scenarios. The effect of varying annual rainfall levels on water savings is further explored through a sensitivity analysis, as illustrated in Figure 1 below.

It is clear from sensitivity analysis how minor changes in annual rainfall quantity will influence the amount of water conserved by RWH systems. Such analysis is most useful in regions where the weather is changing because of climate change or seasonal changes. We simulated the connection between rainfall in the 700 to 1500-millimeter annual range and the water that can be saved, making sure other

things stayed the same. The report finds that water savings increase nearly directly with rising rainfall. At 20% savings for 700 mm of rainfall, the system increases to nearly 40% savings when there is 1500 mm. This new trend points out the vital role climate plays in whether a rainwater harvesting system is successful.

Table 4: Rainfall Sensitivity Analysis.

Rainfall (mm)	Water Savings (%)
700.0	20.0
788.89	22.22
877.78	24.44
966.67	26.67
1055.56	28.89
1144.44	31.11
1233.33	33.33
1322.22	35.56
1411.11	37.78
1500.0	40.0

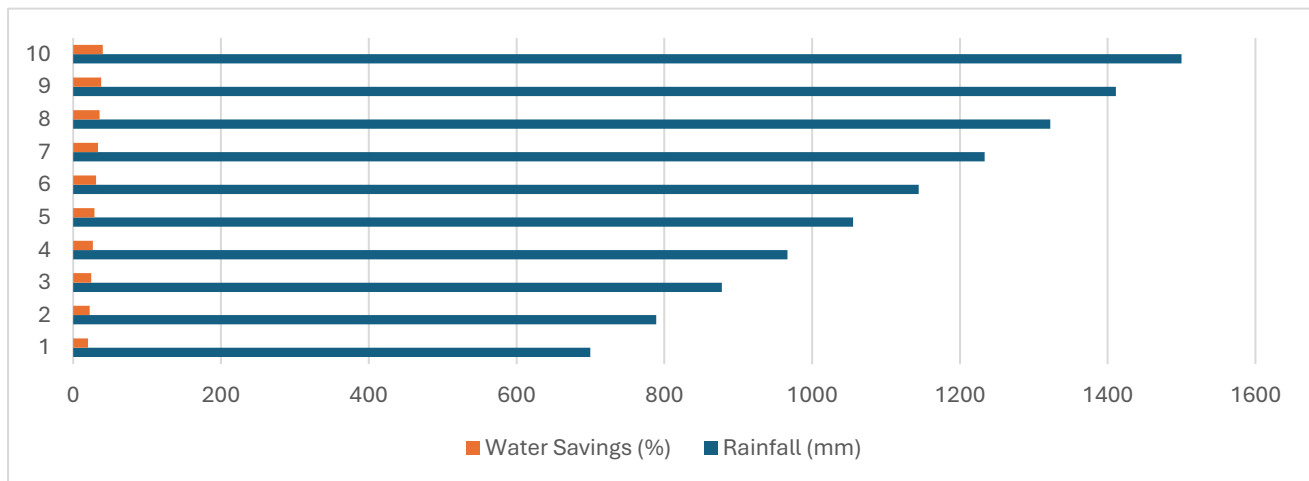


Figure 1: Rainfall Sensitivity Analysis.

Results show that the amount a system stores depends on rainfall variability. Should rainfall amounts drop below projections, the design of even excellent systems might not meet needs. Contrary to drought-prone regions, the same water savings can be found in high rainfall areas using only moderately designed systems. For places with less rain, designers must plan either with bigger roof areas, smaller water tanks or install extra greywater systems to reach the same aims.

Doing this type of analysis provides additional support for adaptive planning practices. Devices can be built to handle the demands of each climate scenario by system designers. In addition, it guides investment choices by showing the places where rainwater harvesting will be the most useful and where the system will most probably thrive. In summary, the results prove the need for local climate

information in RWH designs and suggest that any design should be flexible to address ongoing changes in the environment.

5. DISCUSSION

A review of the sources demonstrates a marked progress in methods used to design and set up rainwater harvesting (RWH) systems for residential homes in cities. Previously, RWH systems were designed using basic approaches and based mainly on past rainfall, estimated formulas or standard practices. In most cases, conventional methods did not address the unique problems found in large cities such as pressure from buildings, rainfall that changes day to day and different water consumption habits. It is clear from the reviewed papers that more researchers are using integrated, optimization-based methods that use hydrological modeling, analyze

economics, track performance in the environment and use spatial intelligence. Bocanegra-Martínez et al. (2014) used a model with several variables to find low-cost solutions, while Sample and Liu (2014) focused on reducing water supply and runoff simultaneously in their model. These studies demonstrate that with sophisticated simulation and algorithms, the important components in a water system—such as tanks, catchment performance and programmed use—can be adjusted to achieve various objectives together. The adoption of this approach reveals a better grasp of urban water systems and a higher demand for infrastructures that can cope with new challenges. Optimizing efficiency and sustainability in RWH systems, these studies guide city planners, engineers and those focused on sustainability when centralized systems are not enough or cannot handle the need.

It is also clear from the study that how well a system works and how long it lasts greatly depends on where it is used. While a rainwater harvesting system has the same idea everywhere, its outcomes depend on typical rain patterns, what materials are used on roofs, the size of the community, energy prices and local policies. Rahman et al. (2020) provide evidence that RWH works differently in different places within the same urban region, by present design curves describing how tanks can become ineffective or significant in various locations. According to this, we should avoid using the same system for all users. Additionally, Angrill et al. (2017) explain that buildings in Mediterranean countries built with high-efficiency systems can still create more environmental harm than good if water is not scarce and energy use for pumping is high. This demonstrates that systems should be good for technology and also good for the local environment and for the local economy. Planners are required to address the difference in rainfall, types of buildings and household energy needs when planning system designs for a location. Even the best RWH plans can fail to provide any real benefit if they are not applied correctly. In addition, these types of tools, as described in the research by Chiu et al. (2015), help assess urban areas at the local scale, resulting in designs that fit in well with the community. Consequently, using site-specific information in system development is essential for today's successful RWH projects.

It also highlights that including rainwater harvesting in other sustainable infrastructure designs should give major benefits, especially when combined with green roofs, greywater systems and technology-based monitoring. For example, the

researched conducted by Maftouni and Askari in 2019 combined RWH with green roofing to boost efficiency in energy consumption and reusing water in residences. The method is designed to save resources and result in quality buildings that have better insulation, can store rainwater and help nature thrive. Similarly, Stang et al. (2021) examine where RWH and GWR systems can be set up for maximum cost and energy savings. Such strategies play a vital role in urban infrastructure design by focusing on several challenges at the same time, including the lack of water, high energy needs, constant high temperatures and runoff. Including IoT technologies helps remotely view what is happening in the system and maintains it reliably, making the RWH system attractive to more people. Because of the smart sensors, users are notified about maintenance, can see the amount of fuel left and change the way they use the tank which improves the system's durability. At the same time, these changes bring challenges such as the need for more complex technology, paying upfront costs and the gap between who can and cannot access the internet. Hence, we must link these advanced systems with various types of policies and sources of financing to promote equal use and acceptance by many people. It is clear from research that using RWH on its own is not as effective as when it is part of a wider urban sustainability system.

While the included studies offer new ideas and technologies, there are still big problems and challenges when it comes to using rainwater harvesting systems across the world. Most importantly, research findings are often not applied as planned in practical settings. Several models and simulations are made with the assumption that ideal conditions exist, but in reality, these conditions are rarely found. As a reality, city households often find it hard to pay for new homes, have little storage space and lack the expertise to properly use new technologies. According to Lade and Oloke (2015), studies on RWH in residential Nigerian areas show that socio-economic flexibility and affordability matter most in low- to middle-income areas. In addition, the way people understand and use RWH systems can influence their success over time, making these issues underappreciated. Not maintaining the system, users failing to adapt or updates to the software can decrease system performance a lot. Difficulties in government policies, a lack of appropriate subventions and insufficient criterion for performance negatively affect the use of RWH in the sector. In addition, only a few studies focus on how systems will age and

what their costs over time will be, preventing a thorough evaluation of their sustainability. Therefore, researchers need to bring different fields to the table and analyze data over time to achieve meaningful future studies. It is also necessary for study results to use the same performance measures to allow better comparison worldwide. To make rainwater harvesting a significant addition to urban water use, we must first deal with these challenges.

From a policy perspective, the findings support the inclusion of rainwater harvesting systems in urban building codes and sustainability rating systems. Financial incentives, standardized design guidelines, and public awareness programs could significantly enhance large-scale adoption.

6. CONCLUSION

The authors have reviewed different rainwater harvesting (RWH) systems used in urban residential buildings, aiming to recognize their designs, strategies for effective use, benefits to the environment and things that may impede implementation. It is clear from the data that rainwater harvesting has grown from being a simple water collection method to a much broader and more advanced sustainability approach. Since rapid urban growth, shrinking water supplies and centralized infrastructure have their limits, RWH is now designed with modern hydrological models, optimization, analytical tools and life cycle assessment in mind. Applying these methods, you can specify the tank, filter, catchment and connection details to achieve both higher efficiency and better results in many contexts. It can be seen from Bocanegra-Martínez et al., Sample and Liu and Rahman et al. that properly using multi-objective

optimization and suitable planning in different situations greatly enhances cost and performance. In addition, when combined with green roofs, greywater recycling and smart sensors, RWH is highlighted in sustainable water strategies instead of being used alone. Consequently, these changes boost their efficiency and contribute to urban resilience, equal access to water and combating climate change.

The field has advanced, but bringing RWH to many residential areas in cities still comes with many challenges to address through different means. Elements such as the high cost to begin, not enough awareness, lack of skilled professionals and scattered regulations are frequent obstacles for wide-scale adoption. In addition, it is important that these systems last by depending on great design, thorough maintenance, the involvement of users and regular check-ups on how they operate. Several studies have shown that local context such as weather, water supply and society, is vital to consider. We should ensure the development of suitable environments by including incentives, setting standards and organizing capacity-building programs. We also require lengthy studies to understand how RWH systems perform and are affected by age, so that what is modeled as efficient can be proven in reality. RWH policies can be promoted in urban planning and awards can be given to highlight it in construction and redevelopment projects. Overall, RWH should not only be considered for emergencies, but a constant and key element in any varied and decentralized regional water plan for cities. If rainwater harvesting is at the center of planning for sustainability, cities experience better water security, do less harm to nature and are supported during changing climate and population trends.

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