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Rainwater Harvesting Design and Optimization in Semi-Arid Mediterranean Climates: A Technical Review with Focus on Türkiye

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ABSTRACT

A comprehensive technical review of current literature regarding rainwater harvesting (RWH) systems in terms of design, feasibility and optimization in Türkiye and similar Mediterranean climates is presented here in. Research has been conducted through a peer-reviewed study process (2010-2026). It was created to provide hydraulic engineers with design specifications and sizing methodologies for use in urban settings. The results indicated that for optimal residential tank size in Türkiye would be dependent upon several factors including roof area (30-270 m²), rainfall (292-1180 mm/year), and demand profile, but generally ranged from 2-21 m³. Particle Swarm Optimization and Linear Programming were identified as the most effective sizing methods to achieve 90-98 % volumetric reliability while minimizing the total lifecycle cost. Potential water savings resulting from implementation of an RWH system range from 20-70 % of domestic water usage, which could result in discounted payback times ranging from 12-36 years based on the configuration of the RWH system and local water pricing structures. The review also emphasized the importance of hydrologic models, filtration requirements and optimization techniques for designing RWH systems in semi-arid Mediterranean climates.

Yarı Kurak Akdeniz İklimlerinde Yağmur Suyu Hasadı Tasarımı ve Optimizasyonu: Türkiye Odaklı Teknik Bir Derleme

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ÖZ

Bu çalışma, Türkiye ve benzeri Akdeniz iklimlerinde tasarım, fizibilite ve optimizasyon açısından Yağmur Suyu Hasadı (YSH) sistemlerine ilişkin mevcut literatürün kapsamlı bir teknik incelemesini sunmaktadır. Araştırma, 2010-2026 yılları arasındaki hakemli çalışmaların incelenmesi süreciyle yürütülmüştür. Çalışma, hidrolik mühendislerine kentsel alanlarda kullanım için tasarım kriterleri ve boyutlandırma yöntemleri sağlamak amacıyla oluşturulmuştur. Sonuçlar, Türkiye'deki optimum konut depo boyutunun çatı alanı (30-270 m²), yağış miktarı (292-1180 mm/yıl) ve talep profili gibi çeşitli faktörlere bağlı olduğunu, ancak genellikle 2-21 m³ arasında değiştiğini göstermiştir. Parçacık Sürü Optimizasyonu ve Doğrusal Programlama, toplam yaşam döngüsü maliyetini en aza indirirken %90-98 hacimsel güvenilirliğe ulaşmak için en etkili boyutlandırma yöntemleri olarak belirlenmiştir. Bir YSH sisteminin uygulanmasıyla elde edilecek potansiyel su tasarrufu, evsel su kullanımının %20-70'i arasında değişmektedir; bu durum, sistem konfigürasyonuna ve yerel su fiyatlandırma yapılarına bağlı olarak 12-36 yıl arasında değişen iskontolu geri ödeme süreleri ile sonuçlanabilmektedir. İnceleme ayrıca, yarı kurak Akdeniz iklimlerinde YSH sistemleri tasarlarken hidrolojik modellerin, filtrasyon gereksinimlerinin ve optimizasyon tekniklerinin önemini vurgulamıştır.

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Introduction

Rainwater Harvesting (RWH) is an important strategy for managing water resources in both Türkiye and throughout the Mediterranean region that are experiencing water shortages due to the impacts of population growth, urbanization, and seasonally varying climate conditions along with increased tourist activities. The semi-arid climate in Türkiye (characterized by variable precipitation, high rainfall during winter months, low rainfall during summer months), provides both opportunities and challenges for designing and implementing RWH systems. As part of this technical review, evidence based guidelines for designing and optimizing RWH systems in Turkish and comparable Mediterranean climates have been compiled by combining methodologies used for engineering design, optimization algorithms and design parameters that were reported in 189 peer reviewed studies.

The use of new optimization techniques-such as linear programming, particle swarm optimization, and stochastic simulations — have made recent improvements to the accuracy of tank size selection and systems configuration decisions (Okoye et al., 2015; Saplioglu et al., 2019). The above computational tools have enabled water engineering professionals to simultaneously optimize several conflicting goals: maximize the reliability of the water supply, minimize both the cost of construction and operation of a water system, and maximize the utilization of available storage in tanks under uncertain rainfall conditions (Russo et al., 2019; Okoye et al., 2015)

The main goal of this review is to combine the current body of technical knowledge relating to: (1) storage tank size optimization methods; (2) hydrologic model types used for arid environments; (3) component specification and hydraulic design criteria; (4) evaluation metrics and reliability analysis; and (5) economic viability framework options. The emphasis of the review will be on numerical design parameters; optimization algorithms that use mathematics; and performance based on empirical data available for residential and small scale urban rainwater harvesting (RWH) systems (Okoye et al., 2015; Ruso et al., 2024).

Material and Methods

Search Strategy and Data Collection

To provide transparent and replicable results, this systematic review followed PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), and thus, all the searches were done according to the PRISMA guidelines. A detailed literature search was executed on three main databases of science; Scopus, Web of Science, and Google Scholar. The research time frame included articles that were available from January 1st, 2010 through January 31st, 2026. The search strategy used a combination of the following terms and Boolean operators: ("Rainwater Harvesting" or "RWH") and ("Optimization" or "Tank Sizing" or "Design Parameters") and ("Turkey", “Türkiye”, "Mediterranean Climate", "Semi-Arid").

Inclusion and Exclusion Criteria

To ensure the technical quality of the review, the identified records were subjected to a two-stage screening process based on titles, abstracts, and full texts.

Inclusion Criteria: (1) Peer-reviewed journal articles and conference proceedings published in English or Turkish; (2) Studies providing quantitative data on tank sizing, water saving potential, or economic feasibility; (3) Research specifically focusing on residential or small-scale urban applications in semi-arid Mediterranean climates.

Exclusion Criteria: (1) Studies lacking technical design parameters (e.g., papers focusing solely on social acceptance without engineering data); (2) Duplicate records; (3) Review articles that did not contribute original data or synthesis relevant to the specific region.

From an initial identification of 189 records, 30 studies met all criteria and were selected for detailed analysis. These studies were categorized based on their primary focus: hydrological modeling, optimization algorithms, and economic assessment. Figure 1 illustrates the PRISMA flow diagram for the study selection process.

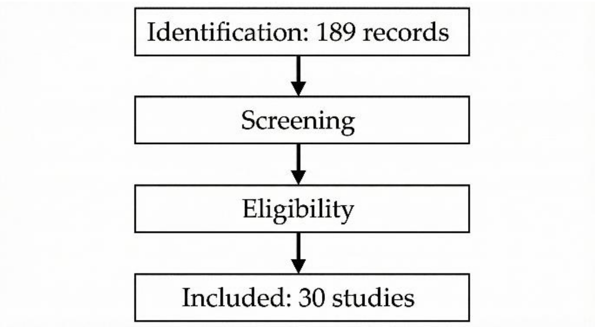

Figure 1. PRISMA flow diagram illustrating the literature selection and screening process.

Hydrological Context and Climate Characteristics

The hydrologic regime in Türkiye has a large degree of spatial and temporal variability. Annual rainfall varies significantly from 292 mm in semi-arid regions located in the interior of Türkiye to 548 mm in coastal Mediterranean regions (Ruso et al., 2019; Abdulla, 2020). A geographic representation of the diverse climates studied in this review can be seen in Figure 2.

Figure 2. Geographical distribution of the selected rainwater harvesting case studies evaluated in this review (highlighting Ankara, Antalya, Aydın, Burdur, Isparta, İzmir, Karabük, and Northern Cyprus).

The Mediterranean climate pattern creates an extreme challenge in designing a Rainwater Harvesting System (RWH); it is characterized as having 60-75 % of total annual rainfall occurring over the six-month period from november through march with a very defined or pronounced drought period during the summer months (Campisano and Modica, 2012; Muklada et al., 2016). Due to the extremely high amount of precipitation that falls during these winter months there needs to be a significantly larger storage capacity to fill the reservoirs prior to the start of the long dry season while at the same time avoid an excess of water overflowing into flood control areas when the rainy weather returns (Campisano and Modica, 2012; Okoye et al., 2015).

A comparative analysis using data from other arid and semi-arid areas in the Mediterranean region shows similar hydrologic limitations to those found in Türkiye. Jordan is another example of a semi-arid Mediterranean country which gets about 200-400 mm of rainfall annually. Also it gets a very large portion of its annual rainfall during the rainy season. Due to the similarities with the other semi-arid mediterranean regions of this study, we will be able to evaluate the effects of droughts on water supplies in Türkiye using data from these areas (Jaradat et al., 2024; Abdulla, 2020). In addition to Jordan, Sicily is also a semi-arid mediterranean coastal area receiving between 400-600 mm of rainfall annually with a similar distribution of rainfall during the winter as Türkiye (Campisano and Modica, 2012; Notaro et al., 2017). Therefore, Sicily provides another valuable analog for designing water resources management systems in Türkiye. Lastly, the northern part of Cyprus, which receives 292-350 mm of rain per year, is the most directly analogous area to evaluate semi-arid coastal conditions in Türkiye (Ruso et al., 2019).

The variable amount of rain that falls each day makes it even harder to determine what size of a system is needed. In analyzing stochastic rainfall in the Mediterranean area, researchers have found that there are large amounts of variability in the rainfall (coefficient of variation greater than 1.5) over a short time period (daily), as well as large amounts of rainfall occurring on the majority of rain days (70-85 %) and very little total rainfall for the year coming from the extreme rainfall events (>50 mm/day) that occur occasionally (Muklada et al., 2016). The variability of rainfall over a short time period necessitates a design approach that includes probability and does not include a design approach based solely on the average rainfall (Muklada et al., 2016; Snir et al., 2021).

System Design Methodologies and Optimization Approaches

Linear Programming Methods

Okoye et al. (2015) stated that the use of Linear Programming (LP) was the most effective and efficient method to date to optimize RWH tank sizes for semi-arid regions. LP is also discussed by Ruso et al. (2024). LP provides a method of optimizing tank sizes through the optimization process which will provide the lowest total system cost while meeting the reliability criteria of the RWH system.

A basic LP model was developed by Okoye et al. (2015) in order to develop an optimized RWH tank size for Türkiye. In this model, the authors used a time-step based approach using daily water balance equations. Decision variables are represented by the volume of the tank, the amount of water flowing over the top of the tank, and the amount of water supplied from the tank when it is empty. The objective function in the model represents the minimum cost associated with both the capital costs (construction, conveyance, filtration) and the operational costs over a 20-30 year design life.

Okoye et al. (2015) noted that the LP model included several critical constraints including: (1) continuity of the daily water balance, (2) maximum capacity of the tank, (3) non-negative storage, and (4) minimum reliability thresholds of 90-95 %.

The LP model was successfully applied to several Turkish case studies and demonstrated that there are significant benefits compared to traditional design methods for determining tank sizes. For example, in a residential analysis conducted by Okoye et al. (2015) on a single family dwelling in Ankara (150 m^2 roof area, 120 L/day demand), the authors determined the optimum tank size to be 8 m^3 with a volumetric reliability of 94 %. This compares to the 12 m^3 tank recommended by traditional design methods. Therefore, the authors concluded that the LP model resulted in a solution that was 33 % less expensive than the traditional design without any compromise in reliability. Additionally, Ruso et al. (2019; 2024) have demonstrated the effectiveness of LP models in determining optimal tank sizes for Northern Cyprus, as they have shown that reliability levels of 90-98 % can be achieved using storage tanks that are 20-40 % smaller than those determined using traditional design methods.

Stochastic and Simulation-Based Approaches

Stochastic modelling is used to capture uncertainty in rainfall through the application of probabilistic representations of the rainfall processes (Snir et al., 2021; Muklada et al., 2016); this permits reliability studies for a variety of climates (Snir et al., 2021; Muklada et al., 2016). To maintain the spatial detail of historical precipitation data while retaining the key features of precipitation, many stochastic models employ Markov Chain Monte Carlo (MCMC) techniques to generate synthetic rainfall sequences which possess historical statistical characteristics of precipitation such as the probability of occurrence of precipitation on a given day, the distribution of precipitation intensities and the temporal autocorrelation of precipitation.

The stochastic water balance model is developed by combining the MCMC rainfall generator with the daily mass balance equation to simulate the long term behavior of the system over thousands of simulations. Thus, reliability metrics including both volumetric and time-based reliability are expressed as probability distributions, and therefore provide confidence intervals for engineering design decisions. For example, Muklada et al. (2016) showed that deterministic designs based on average rainfall in the Mediterranean climate, tend to be conservative by approximately 15-25 percent compared to stochastic approaches with the same reliability target.

The use of a continuous simulation model, using historical rainfall records with at least daily time step resolution and/or sub-daily time step resolution, provides an alternative to the traditional method of generating synthetic rainfall scenarios (Jenkins, 2007). Jenkins (2007) demonstrates that the use of a continuous simulation model, in conjunction with the use of 30+ years of rainfall data, is able to provide reliable estimates of storage size requirements for tanks located within Australia's climatic zones; these are similar to those found in the Mediterranean climates of Türkiye. The study further illustrates that since continuous simulation includes all forms of natural rainfall variability including extremes such as extended durations of dryness and heavy storms, it eliminates the need to make any form of distributional assumption concerning the occurrence of precipitation.

Metaheuristic Optimization Algorithms

It was established that the particle swarm optimization (PSO) methodology can effectively identify the optimum tank sizes for the rainwater harvesting systems; especially where the goal is to find an optimal solution among multiple conflicting goals and nonlinear cost relations (Saplioglu et al., 2019). In order to do so, the PSO methodology uses a population-based search process that simulates the collective behavior of birds to provide near-optimal tank size configurations across the entire solution space. It was also established by Saplioglu et al. (2019), that PSO is very successful in finding solutions to nonlinear objective functions that exist within the problem (such as the economy of scale that exists with construction cost, or the threshold value that defines reliability metrics); such as they were able to determine the optimum tank size combination along with the appropriate first flush diversion and pump specifications in their case study of university buildings in Türkiye using a population based search process with 50-100 iterations that would result in a minimum total cost with a reliability level of at least 95 % for the water supply. Additionally, it was reported by the authors that a comparison of the lifecycle costs obtained using the PSO methodology versus those obtained using linear programming (LP) demonstrated that the inclusion of nonlinear cost factors would result in a reduction in lifecycle costs of 8-12 %.

The authors of Soh et al. (2023) emphasized that the application of multi-objective optimization frameworks allows the ability to address explicitly the multiple objectives that are often present in many engineering applications (for instance, minimizing cost while maximizing reliability, or minimizing flood damage while maximizing water savings).

Additionally, the authors emphasized that the results of the Pareto frontier analysis illustrated a collection of non-dominant options that represent the best possible design options that will allow engineers to select the most suitable option(s) for different stakeholders and localized conditions. Therefore, the results of this research demonstrate how multi-objective optimization can be utilized to develop optimum tank volume configurations for dual-purpose RWH systems by identifying the tank volume configuration that optimizes the trade-off between the amount of water saved and the height of the stormwater flood.

Water Balance Models

The fundamental water balance equation governs all RWH system sizing methodologies, relating storage volume to inflows (rainfall), outflows (demand, overflow, losses), and storage state over time (Campisano and Modica, 2012; Okoye et al., 2015). The daily water balance formulation is expressed as:

$$S(t) = S(t-1) + Q(t) - D(t) - O(t) - L(t) \tag{1}$$

where S(t) is storage volume at time t, Q(t) is harvested rainfall inflow, D(t) is water demand supplied from storage, O(t) is overflow, and L(t) represents losses (evaporation, leakage) (Campisano and Modica, 2012; Okoye et al., 2015). Boundary conditions include: $S(t) \geq 0$ (non-negative storage), $S(t) \leq V$ (tank capacity constraint), and $D(t) \leq \min[S(t-1) + Q(t), \text{Demand}(t)]$ (supply limited by availability) (Okoye et al., 2015).

Harvested rainfall Q(t) is calculated as:

$$Q(t) = P(t)\ x\ A\ x\ \eta \tag{2}$$

where P(t) is daily precipitation depth, A is effective catchment area, and η is the runoff coefficient accounting for losses during collection (Campisano and Modica, 2012; Müftüoğlu, 2024). Runoff coefficients for Turkish roof types range from 0.75-0.85 for tile roofs to 0.85-0.95 for concrete and metal roofs (Müftüoğlu, 2024). First-flush diversion typically removes the initial 1-2 mm of rainfall to improve water quality, effectively reducing η by 5-10 % (Müftüoğlu, 2024).

Behavioral simulation models implement the water balance equation over multi-year time series to evaluate system performance under historical or synthetic rainfall sequences (Jenkins, 2007). The yield-after-spillage (YAS) operating rule—where demand is met from storage before overflow occurs—represents the standard operating policy for domestic RWH systems (Jenkins, 2007). Alternative operating rules, such as yield-before-spillage or controlled release for flood mitigation, require modified water balance formulations (Soh et al., 2023).

Storage Tank Sizing: Technical Parameters and Design Criteria

Optimal Tank Volumes for Turkish Applications

The empirical study of optimal storage tank sizes through the use of examples from Türkiye has demonstrated that the three main variables have an empirical relationship as follows: the size of the roof catchment area, the total amount of annual rainfall in the catchment area and the total amount of water used on a daily basis (Okoye et al., 2015; Ruso et al., 2019; Müftüoğlu, 2024). For residential application in the semi-arid regions of Türkiye (annual rainfall of 300-400 mm), the most suitable volume of tanks ranges between 2-8 m^3 for one family houses (roof area ranging from 100-150 m^2, water consumption ranging from 100-150 L/day) and between 15-25 m^3 for multi-family dwellings (roof area ranging from 300-500 m^2, water consumption ranging from 400-600 L/day) (Okoye et al., 2015; Ruso et al., 2019).

Specific case studies provide quantitative design benchmarks:

- Ankara residential building (150 m^2 roof, 120 L/day demand, 415 mm annual rainfall): Optimal tank size 8 m^3, achieving 94 % volumetric reliability and 45 % water savings (Okoye et al., 2015).
- Northern Cyprus villa (180 m^2 roof, 150 L/day demand, 292 mm annual rainfall): Optimal tank size 12 m^3, achieving 90 % reliability and 38 % water savings (Ruso et al., 2019).
- Aydın detached house (120 m^2 roof, 100 L/day demand, 548 mm annual rainfall): Optimal tank size 6 m^3, achieving 96 % reliability and 52 % water savings (Müftüoğlu, 2024).
- Antalya residential complex (450 m^2 roof, 500 L/day demand, 1180 mm annual rainfall): Optimal tank size 21 m^3, achieving 98 % reliability and 68 % water savings (Himat and Dogan, 2023).

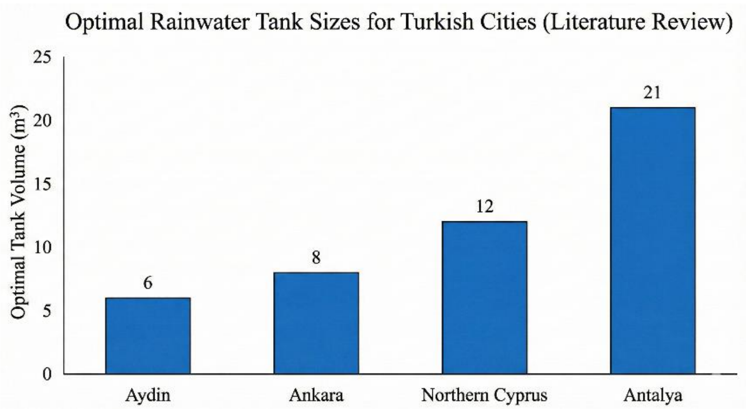

Figure 3. Comparison of optimal storage tank volumes derived from various case studies in Türkiye and Northern Cyprus.

Tank volume and reliability have a decreasing relationship as tank size exceeds an optimal tank volume that is usually around 60 – 70 percent of the average annual harvestable rainfall (Campisano and Modica, 2012; Okoye et al., 2015). Beyond the optimal tank size, there is little increase in reliability from additional tank volume, but there will be a large increase in the cost of the tank (Okoye et al., 2015). For semi-arid climates like those in Türkiye, the optimal tank volume corresponds to approximately 5 – 8 cubic meters of tank storage for a typical residential application (Okoye et al., 2015; Müftüoğlu, 2024).

Sizing Methods Comparison

In a comparative study of the performance of different tank sizing methodologies it has been found that there are significant differences in the way that different methodologies perform (Okoye et al. 2015; Campisano and Modica, 2012). Both linear programming (LP) and particle swarm optimization (PSO) have shown to be more cost-effective and reliable than traditional heuristics such as the demand-fraction methodology, rainfall-fraction methodology and empirical rule based methodologies (Saplioglu et al., 2019; Okoye et al., 2015).

The demand-fraction methodology is based on the idea of using a constant fraction (usually 5-10 %) of the annual demand to determine the required storage volume. This approach will typically result in tanks being over-sized in areas of high rainfall and under-sized in arid areas (Okoye et al., 2015). In comparison to the optimized tank sizes generated from LP methodologies, tank sizes determined by the demand-fraction methodology were found to be 25-40 % larger for Türkiye based applications (Okoye et al., 2015), although they provided comparable levels of system reliability.

Although the rainfall-fraction methodology provides more accurate results in semi-arid conditions than either the demand-fraction methodology or empirical rule based methodologies, it lacks explicit consideration of economics when determining tank sizes (Campisano and Modica, 2012).

As the use of behavioural simulation methodologies can provide the greatest level of detail regarding how a system will operate, as it evaluates the performance of the system under the full range of historical rainfall events (Jenkins, 2007); however, the use of simulation alone cannot identify the optimum tank size without the use of optimization algorithms (Jenkins, 2007).

Therefore, the best practice currently available for designing engineered systems is to combine the use of LP or PSO methodologies for optimization with the use of behavioural simulation methodologies to verify performance (Saplioglu et al. 2019; Okoye et al. 2015).

Reliability and Efficiency Metrics

Reliability in terms of volume is the principal way to measure the performance of RWH systems, which is represented as a percentage of all total demand met by harvesting rainwater during a specific time frame (Campisano and Modica, 2012; Okoye et al., 2015). Reliability of volume in residential applications in Türkiye, for example, can be anywhere from 90-95 percent depending on how much money the owner is willing to spend to save water (Okoye et al., 2015; Ruso et al., 2019). Reliability targets greater than 95 percent require that the tank be significantly larger than those with reliability targets less than 95 percent and this requires an increase in costs that diminishes with each additional percent of reliability (Okoye et al., 2015).

The reliability of time represents the ability of the system to provide water every day (Muklada et al., 2016) and, as such, it provides another piece of information regarding the continuity of supply (Muklada et al., 2016). Due to the fact that there are only two possible outcomes when determining if the system provided enough water on any given day (i.e. yes or no), the reliability of time is always less than the reliability of volume (typically 70-85 percent vs. 90-95 percent) (Muklada et al., 2016). Therefore, while volumetric reliability may be adequate for many applications (residential buildings), time reliability may be the limiting factor in designing RWH systems for applications where continuous supply of water is required (e.g. commercial buildings) (Muklada et al., 2016).

Efficiency of the system is the amount of water that was delivered divided by the total amount of rainwater collected, and it measures how well the storage has been utilized (Campisano and Modica, 2012). RWH systems that have been properly sized for semi-arid climate conditions should be able to operate at an efficiency level ranging from 60-75 percent (Campisano and Modica, 2012) . The losses of water through the system occur primarily due to overflow (15-25 %), first flush diversion (5-10 %), and evaporation or leakage (3-5 %) (Campisano and Modica, 2012; Müftüoğlu, 2024).

Generally speaking, as the size of the tank increases so does the loss of water due to overflow, thus creating a trade-off between the reliability of the system and the overall use of resources (Campisano and Modica, 2012).

Catchment System Design and Hydraulic Components

Roof Catchment Areas and Runoff Coefficients

The size of a rooftop's catchment area is the most important factor determining how much rainwater can be collected from it. The amount of effective space available on the roof is determined by the horizontal surface area of the roof. Single family home rooftops in Türkiye typically measure 80-150 square meters while those of multiple family homes are typically larger and can reach 200-500 square meters (Okoye et al., 2015; Müftüoğlu, 2024).

Turkish roof runoff coefficient values include: Galvanized Iron Sheets (0.90); Tile Roofs (0.75); Concrete Surfaces (0.70). In comparison to the other two types of surfaces evaluated, tile roofing generated more collectible water than did concrete roofing given the same precipitation amounts due to its runoff coefficient being greater than that of concrete surfaces (Müftüoğlu, 2024).

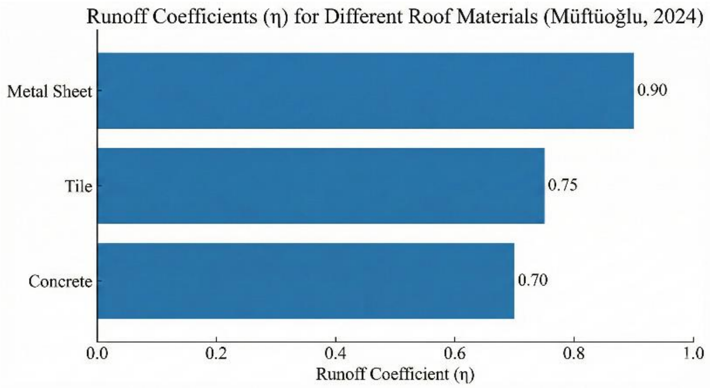

Figure 4. Runoff coefficients for common roof materials in Turkish residential buildings (adapted from Müftüoğlu, 2024).

Filtration and First-Flush Systems

The main purpose of the First-Flush Diversion Systems is to remove the first rainfall volume that has the greatest amount of contaminants from rooftops (Müftüoğlu, 2024). In terms of design recommendations for Türkiye, the author suggests using a diversion volume of 1 – 2 mm (1 – 2 L/m²) of storage that would be equivalent to 100 – 200 L of storage for the average residential roof area.

For filtration, Müftüoğlu (2024) recommends a standard multi-step process including: (1) coarse screen filter (1 – 2 mm mesh) at the inlet of the gutters; (2) finer filtration (0.2 – 0.5 mm mesh) before the water enters the tank; and (3) if applicable, disinfection for potable use. It is noted by the study that for the majority of non-potable uses of harvested rainwater (i.e., flushing toilets or irrigation), only the first two steps will be necessary. However, while pressure filtration systems (pore sizes 5 – 20 μm) can provide higher quality water than gravity fed systems, they also require more energy and maintenance. Therefore, according to Müftüoğlu (2024), gravity fed systems with 0.5 mm mesh screens provide the best cost effective and practical solution for residential rainwater harvesting in Türkiye. This is because they meet the required water quality standards while providing the simplest form of operation.

Conveyance and Pumping Systems

According to Müftüoğlu (2024), for a conveyance piping system designed to support the peak inflow rate into a water storage tank; however, it should be sized to provide sufficient head loss reduction that minimizes costs of installing piping; and at the same time, the sizing process should take into consideration the safety requirements of the piping system. For residential use, a common approach is to select PVC or HDPE pipe sizes ranging from 75 to 100 mm in diameter. Additionally, as an aid to the maintenance of clean conditions throughout the piping system, a slope of 1 to 2 percent is suggested to assure that the self-cleaning velocity of the fluid flowing through the system exceeds 0.6 m/s, which will preclude sediment from collecting in the system.

As for the pump design criteria, the system design needs to account for two types of head that need to be addressed: the static head, which includes the tank depth plus the height that the system needs to deliver water to the point of application, plus the dynamic losses due to friction and other fittings that the system encounters. In most cases for residential installations that have total heads ranging from 3 to 5 meters, a centrifugal type pump that has a rated horsepower of 0.5 to 1.0 kW and a flow capacity of 30 to 50 liters per minute will suffice. Additionally, using variable speed pumps with pressure sensors allow the system to operate on-demand, which reduces energy usage by about 20-30 % when compared to fixed speed systems; however, the variable speed pump can also contribute to maintaining pressure stability and extend the service life of the equipment (Müftüoğlu, 2024).

Dual supply systems require an automated switch control system to provide continuous supply to users once the rainwater in the storage tank is depleted (Judeh et al., 2022). The most common methods used to detect low levels of storage are float switches or pressure sensors that automatically turn on the municipal backup supply. Importantly, backflow prevention devices, i.e. air gaps or check valves, must be installed in dual supply systems to prevent cross-contamination of the municipal water distribution network and to meet all public health standards.

Performance Analysis and Water Savings Potential

The range of potential water savings from rainwater harvesting in Türkiye is estimated to be between 20-70 % of total domestic use based upon the size of the collection system, amount of rainfall collected and demand patterns (Okoye et al., 2015; Ruso et al., 2019; Abdulla, 2020; Müftüoğlu, 2024) for non-potable uses, such as flushing toilets, washing clothes, and irrigating plants which typically comprise 40-50 % of all residential demand (Okoye et al., 2015;

Müftüoğlu, 2024); thus properly designed systems can reduce total demand by 60-90 % in Mediterranean climate types (Okoye et al., 2015; Müftüoğlu, 2024).

Water savings from rainwater harvesting systems show significant variability over time. Typically, between November-March, rainwater harvesting systems will produce water savings of about 80-95% of total demand. However, due to the limited amount of rainfall available during this period, the production of water savings drops significantly during the dry summer months (June-September) and may only account for about 10-30 % of total demand (Ruso et al., 2019; Müftüoğlu, 2024). Thus, despite the ability of rainwater harvesting systems to provide water savings during certain times of the year, these systems continue to rely heavily on municipal supplies to meet base load demand during the dry summer months (Ruso et al., 2019).

In addition to providing water savings at specific points in time, rainwater harvesting systems also provide an opportunity to conserve potable water. In particular, for those households or commercial/industrial users with a high demand for water during the hot and dry summer months, such as for irrigation, rainwater harvesting systems have the potential to provide the largest portion of their water needs during the cooler and wetter months (Müftüoğlu, 2024). This results in a temporal mismatch between water availability and demand.

In terms of comparative analyses of rainwater harvesting system effectiveness across different parts of Türkiye, it has been found that there exists a significant correlation between the level of rainfall received each year and the amount of water savings achieved through rainwater harvesting systems (Ruso et al., 2019; Abdulla, 2020; Müftüoğlu, 2024). Specifically, for coastal areas of Türkiye with annual rainfall levels above 800 mm, moderate storage tank sizes of 8-12 m^3 can provide sufficient water savings to meet 60-70 % of non-potable household demand (Himat and Dogan, 2023). On the other hand, interior regions of Türkiye, such as the semi-arid regions, receive much lower levels of rainfall, averaging around 300-400 mm per year. As a result, even large storage tanks of 12-18 m^3 can only provide water savings of 30-45 % (Okoye et al., 2015; Ruso et al., 2019).

Based on these findings, it appears that rainwater harvesting systems are most economically viable for regions of Türkiye with annual rainfall levels greater than 500 mm (Campisano and Modica, 2012; Abdulla, 2020).

In terms of maximizing the efficiency of rainwater harvesting systems, effective demand management is essential. By prioritizing the use of rainwater harvested water for low-quality uses, such as toilet flushing and irrigation, rather than high-quality uses, such as drinking and cooking, the amount of water saved can be maximized, while minimizing the amount of treatment required to make the water safe for reuse (Judeh et al., 2022). Additionally, smart control systems that continuously monitor the current state of the water system and adjust the allocation of stored water to meet changing demands can provide additional water savings of up to 10-15% over simple priority-based allocation strategies (Behzadian et al., 2018).

Economic Feasibility and Lifecycle Cost Analysis

Residential Rain Water Harvesting Systems in Türkiye have three main factors influencing their long term economic viability - the cost of the initial investment (capital) for the system; the annual cost for municipal supplied water; and the anticipated service life of the system (Abdulla, 2020; Himat and Dogan, 2023; Okoye et al., 2015). There are many variables to consider when evaluating the costs of a residential Rain Water Harvesting System, including the cost of the storage tank(s), pump(s), treatment unit(s), piping, other components, and the cost of installation (Okoye et al., 2015; Himat and Dogan, 2023). The cost of each component of a residential Rain Water Harvesting System is typically dependent upon the storage capacity of the tank(s), as well as the design/manufacture of the system (Okoye et al., 2015; Himat and Dogan, 2023). For instance, the cost of a residential Rain Water Harvesting System, depending on storage capacity, ranges from $800 to $1,500 per cubic meter (Okoye et al., 2015; Himat and Dogan, 2023). A residential Rain Water Harvesting System having 8 cubic meters of storage capacity would thus cost anywhere from $6,400 to $12,000 (Okoye et al., 2015; Himat and Dogan, 2023), with the storage tank itself accounting for 50 % to 60 % of the cost of the entire system (Okoye et al., 2015; Himat and Dogan, 2023).

The costs associated with operating a residential Rain Water Harvesting System include the cost of pumping the collected water into the storage tank(s), estimated to be in the order of $20-$40 annually (Himat and Dogan, 2023); the cost of performing routine maintenance tasks associated with maintaining the operation of the system, estimated to be in the order of $50-$100 annually (Himat and Dogan, 2023); and the cost of replacing various components of the system over its 25-year service life (Himat and Dogan, 2023). Overall, during its 25-year service life, the cost of operating the system represents approximately 15 % to 25 % of the overall cost of owning and operating a residential Rain Water Harvesting System (Himat and Dogan, 2023), demonstrating that the majority of the cost of owning and operating a residential Rain Water Harvesting System relates to the purchase of the system and the ongoing costs of maintaining it.

Residential rainwater harvesting systems are typically evaluated for their economic viability based on discounted cash flow models utilizing discount rates of 5 % and 8 %, typical of those utilized when evaluating the economic feasibility of residential water infrastructure in

Türkiye (Himat and Dogan, 2023). Utilizing the above stated assumptions, the estimated simple pay-back periods for residential rainwater harvesting systems in Türkiye are estimated to be between 12 – 36 years, with the primary factor influencing the payback period being the local water tariff rates and the size of the system (Okoye et al., 2015; Abdulla, 2020; Himat and Dogan, 2023).

Systems located in coastal regions of Türkiye, such as Antalya, have the potential for achieving shorter simple payback periods (12 – 15 years), due to higher municipal water rates and larger annual rainfall (approximately 1180 mm/year) (Himat and Dogan, 2023).

Semi-arid inland areas of Türkiye have low municipal water tariffs (\$0.80 – 1.20/m^3), resulting in long simple payback periods (25 – 35 years) for rainwater harvesting systems, often exceeding the expected life span of the system (Okoye et al., 2015; Ruso et al., 2019).

Net Present Value (NPV) calculations that account for the time value of money demonstrate that residential rainwater harvesting systems are economically viable (NPV > 0) only in those areas of Türkiye receiving high levels of rainfall, and where the municipal water tariff exceeds approximately \$1.50/m^3 (Himat and Dogan, 2023). For many of the inland areas of Türkiye, the current municipal water tariffs result in a negative NPV calculation, implying that either an increase in water tariffs, a decrease in capital costs for the systems, or a combination of both and/or some form of incentive provided by government policies would need to occur to render the systems economically viable (Okoye et al., 2015; Himat and Dogan, 2023).

The sensitivity analyses indicate that the water price is the most significant variable affecting the economic viability of the systems. A 50 % increase in the water tariff reduces the simple payback period by approximately 30 – 40 % (Himat and Dogan, 2023). The cost of the storage tank is the next most significant variable affecting the economic viability of the systems, with a 30 % decrease in the cost of the storage tank potentially attainable through economies of scale, or through innovations in materials used for the storage tanks, improving the NPV by 25 – 35 % (Himat and Dogan, 2023). The impact of rainfall variability on the economic viability of residential rainwater harvesting systems is relatively small compared to the effects of water price and storage tank cost. For example, a 20 % increase or decrease in annual rainfall results in a 10 – 15% change in NPV values (Himat and Dogan, 2023).

Comparative Analysis: Mediterranean and Semi-Arid Regions

Comparative evaluation of rainwater harvesting performance in Mediterranean and semi-arid regions indicates common design practices regardless of regional differences in rainfall and demand patterns (Notaro et al. 2017; Campisano and Modica, 2012; Abdulla, 2020; Jaradat et al., 2024). The similarity in practices suggests that well-developed design heuristics can be adopted by other regions with similar climates if they account for their specific local rainfall distributions and demand profiles.

A case study conducted in Sicily demonstrates that optimal residential tank size is in the order of 6-12 cubic meters per dwelling, which is in line with recommendations published for the case of Türkiye (Notaro et al., 2017; Campisano and Modica, 2012). The agreement in optimal tank size supports the application of Mediterranean based design criteria to rainwater harvesting systems in Türkiye.

However, Jordan exhibits more pronounced aridity (rainfall 200-400mm/year), hence it is necessary to provide larger storage tanks (in the order of 10-18 cubic meters) to ensure comparable reliability to that of Mediterranean regions (Jaradat et al., 2024; Abdulla, 2020). The increase in storage tank size is related to the decrease in rainfall and increase in rainfall variability between years.

The ratio of the optimal tank volume to the annual amount of harvestable rainfall has been suggested as a dimensionless design parameter enabling cross-regional comparisons of system sizing (Campisano and Modica, 2012). For Mediterranean regions the ratio of the optimal tank volume to the annual amount of harvestable rainfall is in the order of 0.15-0.25 (Campisano and Modica, 2012; Notaro et al., 2017); therefore the corresponding optimal storage tank corresponds to approximately 15-25 % of the annual harvestable rainfall (Campisano and Modica, 2012; Notaro et al., 2017). In drier areas such as Jordan and the dry parts of Türkiye, the ratio is in the order of 0.25-0.35 because there is a greater concentration of rainfall in time and space and also due to the higher rainfall variability between years (Jaradat et al., 2024; Abdulla, 2020).

Reliability – cost trade-off relationships have similar properties for all Mediterranean climates; where the marginal cost of providing additional reliability is large when the volumetric reliability is higher than 90 – 95 % (Campisano and Modica, 2012; Notaro et al., 2017). Therefore the reliability – cost relationship suggests that a target reliability range of 90 – 95 % would represent an economical optimum for the design of residential rainwater harvesting systems in Mediterranean climates; thus balancing the benefits of water savings against the costs of capital investments (Campisano and Modica, 2012).

Only in cases of extreme water prices (> \$2.50 /m³) or severe supply restrictions as those experienced in some arid areas (Abdulla, 2020), will reliability levels above 95 % be economically justifiable.

Projections of climate change for the Mediterranean region indicate increased rainfall variability and longer drought periods resulting in reduced reliability of rainwater harvesting systems by around 10 – 20 % by 2050 according to moderate emission scenarios (Jaradat et al., 2024). This projected trend implies that systems designed solely using past climate data could potentially perform poorly over the coming decades and therefore may require either increased storage volumes or a willingness to accept lower reliability levels (Jaradat et al., 2024).

Optimization methods that take into consideration climate uncertainty have been proposed to identify tank sizes that maintain reasonable performance levels over a range of potential future climate scenarios (Soh et al., 2023).

Synthesis of Optimization Methodologies and Economic Viability

Although the hydrological inputs are influenced by similar geographical conditions, the review finds a significant distinction in design methodology approaches. The advanced optimization techniques such as linear programming (LP), particle swarm optimization (PSO), have been shown to produce superior results compared to the heuristics (i.e. demand fraction), with an 8-12 % reduction in lifecycle cost and at least 90 % level of reliability (Saplioglu et al., 2019; Okoye et al., 2015). Nevertheless, the economic viability of these optimized systems in Turkey depends largely upon the price municipalities charge for water. Literature indicates that it will require a tariff of approximately $1.50/m³ for the system to be financially viable without subsidizing (Himat and Dogan, 2023). Below this tariff rate, the payback period can extend up to 25 years or longer, which makes residential rainwater harvesting (RWH) technically efficient but economically unattractive for most users (Ruso et al., 2019; Himat and Dogan, 2023).

Advanced Applications: Dual-Purpose Systems for Flood Mitigation

Dual-purpose rainwater collection systems which are a combination of both collecting rainwater and managing runoff from storms, have become a growing area of interest as they offer many benefits in regards to providing clean water supplies for communities and help to manage flooding in cities, especially in urban areas of Türkiye (Snir et al., 2022; Soh et al., 2023). Rainwater collection systems which provide multiple purposes use regulated orifice discharge mechanisms to conserve space to collect water from future rains and maximize water conservation (Snir et al., 2022; Soh et al., 2023).

In regards to controlling and optimizing dual-purpose rainwater collection systems, there is a need to weigh and meet two main conflicting goals: conserving enough stored water to maintain the dependability of your water supply and discharging the stored volume of water to handle the increased storm event flow (Soh et al., 2023). The results of Snir et al. showed that when using decentralized rainwater collection systems equipped with optimized algorithms for regulating water flow into sewers, you can expect to see about 20 – 40 % less urban drainage flow through the sewers during small to moderate-sized storm events (10 – 25 mm) while also meeting water supply dependability requirements of 85 – 90 % (Snir et al., 2022).

The control algorithm which was applied in the study utilizes short-term weather forecasting to pre-discharge water from the tank before the storm occurs so that there will be enough storage in the tank to capture the storm but it does not compromise the water conservation performance (Snir et al., 2022). When utilizing this type of dual function capability in combined sewer systems in urban areas of Türkiye, the dual-function capability will greatly increase the financial feasibility of investing in rainwater collection systems by decreasing the size of the necessary storm drain infrastructure and associated costs (Snir et al., 2022).

When developing robust optimization models for dual-purpose rainwater collection systems, the uncertainty in precipitation data affecting the ability to produce water for the community and uncertainty in storm intensities affecting the ability to mitigate flooding are explicitly accounted for (Soh et al., 2023). Through Pareto Frontier Analysis, it has been shown that systems which were optimized primarily for producing water will only result in minimal benefits for mitigating flooding, while systems optimized primarily for flood mitigation will lose approximately 30 – 40 % of possible water conservation benefits (Soh et al., 2023).

System design that balances the objective functions of water supply and flood mitigation can achieve approximately 70 – 80 % of the maximum achievable benefits for each objective function simultaneously, with typical system design having tanks that are 20 – 30 % larger than the design size needed to optimize the system for water supply alone (Soh et al., 2023). This highlights the need for multi-objective optimization in designing and implementing urban rainwater collection systems.

Operating the dual-purpose systems will require changes to the existing operating procedures and will require new control equipment beyond what would be required in traditional rainwater collection systems (Snir et al., 2022; Soh et al., 2023). Capital cost for real-time control systems with features such as integrating weather forecast information, automatically opening and closing valves, and remotely monitoring the systems will be approximately 15 – 25 % higher than that of a passive system (Snir et al., 2022). However, in urban areas where the cost of managing stormwater run-off is extremely high, the total benefits of both conserving water and mitigating flooding may be able to justify the added cost (Snir et al., 2022; Soh et al., 2023).

Design Recommendations and Engineering Guideline

Based on synthesis of the reviewed literature, the following design recommendations are provided for RWH systems in Turkish and comparable Mediterranean climates:

Tank Sizing:

- For residential projects located in semi-dry areas with precipitation rates ranging from 300-400 mm/yr: 6-10 m³ (single-family home = 100-150 m² roof area) and 15-25 m³ (multi-family building = 300-500 m² roof area) (Okoye et al., 2015; Ruso et al., 2019).
- For coastal Mediterranean areas (>600 mm/yr rainfall): 4-8 m³ (single-family home) and 10-18 m³ (multi-family building) (Campisano and Modica, 2012; Notaro et al., 2017).
- The target volumetric reliability is: 90-95 % for cost optimal designs (Campisano and Modica, 2012; Okoye et al., 2015).
- The tank volume should not exceed 25 % of the annually collectible rainfall to limit excessive excess flow losses (Campisano and Modica, 2012).

Optimization Methodology:

- Perform linear programming or use particle swarm optimization to size tanks, while using a behavioral model to simulate performance (Saplioglu et al., 2019; Okoye et al., 2015).
- Use a water balance model with at least 10 years of historical rainfall data in daily time steps (Okoye et al., 2015; Jenkins, 2007).
- Analyze the sensitivity of water prices, rainfall variations and changes in demand to the system's performance (Himat and Dogan, 2023).

Catchment and Conveyance:

- Roof runoff coefficients are as follows: 0.90 for metal; 0.75 for tile roofs; 0.70 for concrete roofs (Müftüoğlu, 2024).
- Diversion of first flush is 1-2 mm of rainfall or in terms of volume approximately 100-200 litres per average residential roof area (Müftüoğlu, 2024).

- Gutters should be sized to provide a minimum of a 100-150 mm/hr peak intensity, with an additional 20-30 % freeboard (Müftüoğlu, 2024).
- The conveyance pipes used for conveying stormwater should have diameters of 75-100 mm (PVC/HDPE) and slopes of at least 1-2 % (Müftüoğlu, 2024).

Filtration and Treatment:

- Coarse filtration (1-2mm) of roof surface runoff by means of gutter screens followed by a second stage of finer filtration (0.2-0.5mm) immediately prior to entering into the storage tank (Müftüoğlu, 2024).
- Screened (0.5 mm) gravity fed systems for use in non-potable applications (Müftüoğlu, 2024).
- Potable applications may require additional treatment such as UV disinfection or chlorine addition to achieve a minimum 0.5 - 1.0 mg/L free residual (Judeh et al., 2022).

System Integration:

- Dual-supply configuration with automatic switching between rainwater and municipal backup (Judeh et al., 2022).
- Backflow prevention mandatory for municipal connection (Judeh et al., 2022).
- Variable-speed pumps with pressure control for energy efficiency (Müftüoğlu, 2024).

Economic Considerations:

- RWH is a financially feasible option when water pricing is at least $1.50/m³ and rainfall totals 500mm of precipitation annually (Himat and Dogan, 2023).
- When water prices or rainfall in an area do not allow RWH to be financially feasible then it will require policy incentives (such as subsidies or rebates) to make it financially feasible (Okoye et al., 2015; Himat and Dogan, 2023).
- Prioritize RWH for new developments to take advantage of the fact that installation costs will be between 30-40 % lower than retrofit installations (Himat and Dogan, 2023).

Research Gaps and Future Directions

In spite of significant advances in RWH system design and optimisation there are still a number of areas of study which require further investigation:

- Climate Change Adaptation: Although there have been some studies into RWH system design to take account of potential future changes in rainfall patterns and drought duration (Jaradat et al., 2024) very few studies have examined how such changes will affect the performance of RWH systems over time (Soh et al., 2023). The need for robust optimisation tools that can be used to determine RWH system designs based on current estimates of climate uncertainty is becoming increasingly important as an increasing number of RWH systems come into operation.
- Water Quality and Treatment: Although the majority of studies relating to RWH systems in Türkiye have focused on determining suitable system sizes and hydraulic designs for RWH systems, most studies have paid little if any attention to the effects of the characteristics of roof type and local climatic conditions on water quality and required treatment processes (Müftüoğlu, 2024). Furthermore, no comprehensive water quality monitoring has been undertaken at a national level in Türkiye to provide data to support the design of water treatment systems (Müftüoğlu, 2024).
- Smart Control Systems: Advanced control methods for dual purpose RWH systems have shown great potential for use in smart RWH systems (Snir et al., 2022; Behzadian et al., 2018), however, studies examining the practicality of implementing such smart control methods for RWH systems in Türkiye have yet to be published (Behzadian et al., 2018). Research is required to develop low-cost sensor networks, integrate forecasts into smart control systems and investigate the benefits of using adaptive control methods to improve the widespread uptake of smart RWH systems (Behzadian et al., 2018).
- Social and Institutional Dimensions: Studies examining the technical feasibility of RWH systems dominate the current literature, whilst few studies have examined the role of user acceptance, behavioural factors and institutional barriers to RWH adoption in Türkiye (Himat and Dogan, 2023). To develop policies to support RWH adoption, interdisciplinary research is required to examine the technical, economic and social dimensions of RWH (Himat and Dogan, 2023).
- Life Cycle Assessment: There is a lack of comprehensive assessments of the environmental impacts associated with RWH systems during all phases of their life cycles, including material usage, operational emissions and end-of--life disposal (Morales-Pinzón et al., 2012). The completion of life cycle assessments of RWH systems will allow them to be compared with other alternative water management strategies (Morales-Pinzón et al., 2012).

- Coordinating Decentralized Systems: The research on coordinating decentralized RWH systems for a neighborhood or district level to manage both potable water and stormwater at the same time is currently still in its early stages but has a large potential as a whole (Snir et al., 2022). Techniques can be created to find the possible synergy's of optimizing multiple decentralized RWH systems at once (Snir et al., 2022).

Conclusion

The results of the above Integrated Technical Review represent an aggregation of the present state-of-the-art in engineering-related knowledge about the design and optimization of rainwater harvesting (RWH) systems for residential applications in Türkiye and in Mediterranean climates.

Some important findings of this synthesis include:

1. The appropriate size of a storage tank for RWH application in the residential sector in arid-semiarid regions of Türkiye varies between 6–10 cubic meters, while the appropriate size in coastal areas where there are high precipitation values ranges between 4–8 cubic meters. Both sizes result in volumetric reliabilities ranging from 90 to 95 percent, while also producing between 30–50 percent savings in the consumption of domestic potable water (Okoye et al., 2015; Ruso et al., 2019; Müftüoğlu, 2024).
2. Optimization methods such as linear programming and particle swarm optimization result in smaller tank sizes than conventional design practices, while reducing costs by 20–40 percent (Okoye et al., 2015; Saplioglu et al., 2019).
3. Depending on the amount of local precipitation (typically >600 mm/yr) and type of use (potable versus non-potable uses such as toilet flushing and irrigation) domestic water conservation via RWH systems can vary between 20–70 percent of the total water used in a house (Okoye et al., 2015; Müftüoğlu, 2024).
4. The economic viability of installing RWH systems is contingent upon water prices exceeding $1.50/cubic meter and annual rainfall amounts of >500 mm/year (Himat and Dogan, 2023). Regions with lower prices and/or rainfall amounts may need additional financial incentives (such as tax credits or low-interest loans) to encourage people to adopt them (Okoye et al., 2015; Himat and Dogan, 2023).
5. Urban RWH systems capable of providing both a source of domestic water supply and flood mitigation can provide combined benefits that can make up for the expenses of developing these systems, but require sophisticated control systems and storage tank sizes

that are 20–30 percent larger than those necessary for single-purpose RWH systems (Snir et al., 2022; Soh et al., 2023).

6. Some general design recommendations include the use of daily time-step optimization models, multi-stage filtration systems, dual-supply configurations (with municipal backup supplies), and sensitivity analyses based on different design parameters (Campisano and Modica, 2012; Okoye et al., 2015; Müftüoğlu, 2024).

As a result of the referenced studies, a technically feasible framework for optimizing the performance of RWH systems in Türkiye and in other similar Mediterranean climates has been developed. Nonetheless, to foster the adoption of RWH systems, a favorable policy environment must be established to support the installation of RWH systems and to provide financial incentives to individuals and organizations to install RWH systems. It is equally important to develop institutional frameworks that enable the effective implementation of RWH systems. Future research should focus on adapting RWH systems to climate change, determining the effect of using collected rainwater for irrigation and other uses on the quality of the water, developing smart control systems to manage both the quality and quantity of rainwater that has been harvested, and encouraging interdisciplinary research to assess both the technical and non-technical elements of successfully implementing RWH systems (e.g., economics, social considerations).

Conflict of Interest Statement

The author of the article declares that there is no conflict of interest.

Contribution Statement Summary

The author declares sole responsibility for the entirety of the article.

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