



Efficient Roof Selection in Rainwater Harvesting: Hybrid Multi-criteria and Experimental Approach

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Abstract

This study aimed to investigate the effects of different roof configurations on the quality of harvested rainwater (HRW) for sustainable irrigation in agriculture. Three roofing materials (i.e. shingle, galvanized metal, and clay tile) and three roof pitch angles (i.e. 5°, 30°, and 42°) were used at pilot-scale. HRW was characterized in order to determine the roof type and roof slope effect on the HRW quality. HRW from galvanized metal roofs was of higher quality in terms of turbidity and pathogen microorganisms. HRW from shingle and clay tile roofs was treated with a sequential ultrafiltration (UF) membrane and ultraviolet (UV) disinfection system to meet the European Union (EU) water reuse standards for irrigation. The decision-making mechanism was used to select the most appropriate roof configuration. The results showed the significance of financial (21.89%) and environmental (19.75%) aspects. Also, the *Escherichia coli* (*E.coli*) content (7%) is the most determinant factor in HRW, followed by the operational cost (6.78%), and reduced runoff (5.73%). Among the roof configurations, galvanized metal roofs, specifically the metal roof with 5°, outperformed others due to their structural, technical, and environmental advances.

Keywords Circular economy · Fuzzy AHP · TOPSIS, rainwater harvesting · Ultrafiltration · UV disinfection

1 Introduction

Rainwater harvesting (RWH) is a multi-component strategy in urban areas that involves capturing water from existing facilities, such as rooftops, gutters, basic filters, first flush, storage tank, and intake to the treatment plants (Yadav et al. 2024). Since the agriculture sector is the main water consumer with 70% of global water consumption, using HRW in agricultural irrigation is of great importance in ensuring the sustainability of the agricultural production (WWAP, 2019). Obviously, numerous factors can affect the quality of HRW e.g., De Buyck et al. (2021) identified atmospheric deposition and leaching from roof materials

as the two major mechanisms contributing to roof runoff contamination. In another study, Lee et al. (2012) focused on roof materials and environmental conditions and concluded that local temperature and atmospheric pollution had important impact on the quality of HRW. Some studies reported that roof material and slope are also influential factors for the quality and quantity of HRW (Farreny et al. 2011). Since roofs are exposed to the sun and atmosphere, roofs accumulate large amounts of suspended solids over time. Zhang et al. (2020) further highlighted the impact of roof characteristics, i.e. material type and slope of the roof surface on the water quality of HRW. Although rainwater is considered one of the cleanest available supplemental water resources, studies showed that HRW is often required to be treated due to rich nutrients, microbial pathogens and heavy metals (Zhang et al. 2014).

Rainwater treatment techniques are mainly categorized as physical, chemical, and biological. These techniques incorporate different layers of processes such as granular activated carbon (GAC), chlorination, ozonation, and UV disinfection, sand filtration, membrane separation. Marszałek and Dudziak (2021) combined a cross-flow UF system with UV disinfection to treat rainwater obtained from different roofs. They found that coliform bacteria and *E.coli*. could be completely removed from HRW by coupling UF and UV. Ortega Sandoval et al. (2019) used hollow-fiber microfiltration (MF) and UF membranes and obtained permeates which were appropriate for toilet flushing and fire extinguishing. Yu et al. (2021) acquired drinking water from rainwater by using sequential GAC, nanofiltration, and chlorination processes. Moreira Neto et al. (2012) provided treated rainwater that has compatible quality with the recommendations by utilizing slow sand filtration followed by chlorination.

Along with rainwater characterization and applied treatment, a wide range of criteria should also be considered in the selection of optimal roof type configurations, especially concerning the circular economy principles. The research community has oriented its attempts toward more sustainable and circular practices which embraces the transition to regenerative approaches from a traditional linear “take, make, dispose” model. Antwi-Afari et al. (2021) addressed the circularity gap by utilizing the strengths, weaknesses, opportunities, and threats (SWOT) analysis to exhibit the potential implications regarding circular economy strategies in the construction industry. Superti et al. (2021) proposed the 10R scheme encompassing various interventions, such as R0: Refuse/Rethink, R1: Reduce, R2: Resell/reuse, R3: Repair, R4: Refurbish, R5: Remanufacture, R6: Repurpose, R7: Recycle, R8: Recover, and R9: Re-mine. These studies not only demonstrated the positive impact of the effective use of materials with minimal degradation of natural resources but also opportunities to satisfy the United Nations (UN) sustainable development goals (SDGs).

Given various criteria, different multi-attribute decision-making mechanisms having the ability to handle such complex problems have been proposed in the relevant literature. Farreny et al. (2011) assessed four roof types composed of different material types, i.e. clay tiles, metal sheet, polycarbonate plastic, and flat gravel, and characterizing various roughness under different environments such as a region surrounding by forests and urban areas with particular tree-effect conditions. Considering both quantity (e.g. precipitation height) and quality (e.g. electrical conductivity (EC), pH, total suspended solids (TSS), total organic carbon) evaluation criteria, they concluded that sloping smooth roofs with metal sheet and/or polycarbonate plastic were the best option to promote RWH, especially compared to flat roofs. Some studies only assessed water quality aspects from rainwater tanks. Despite efforts devoted to assess water quality from rainwater tanks (Rahman et al. 2012), there is a gap in the relevant literature on the HRW characterization from commonly used roof

materials and roof slopes, and the treatment methods of HRW. Also, the existing body of knowledge still lacks the implementation of MCDM analysis to determine the most appropriate roof configuration, even though some scholars practiced these techniques on RWH site selection (Ezzeldin et al. 2022).

The objective of this study is to design a robust decision-making mechanism for selecting the most appropriate roofing material and roof pitch angle using expert elicitation together with UF-UV disinfection system (compared with the EU standards for water reuse) for irrigation reuse in Turkey, a water scarce region. The contributions of the present research also cover the hybrid implementation of MCDM techniques to roof selection mechanism consolidated by the data attained from pilot-scale experiments, which is the initial attempt in the RWH literature. The selection rationale, for the first time, is established concerning circularity objectives, aiming to orient efforts toward to limited natural resource consumption in line with the SDG3, 6, 7, 13, 15, and 17.

2 Materials and Methods

2.1 Research Framework

This research conducted an extensive literature survey to extract the decision criteria (Table S1 in the Supplementary File) ensuring the comprehensive assessment of the alternative roof configurations. Based on circular economy principles, MCDM analysis was performed to find the optimal roof configuration for RWH. The criteria weights were determined by the fuzzy AHP and the roof types were prioritized using the TOPSIS. To achieve actual scores, not only qualitative analysis made via the experts but also literature survey and bilateral negotiations with private sector representatives were conducted. The following sub-sections explain the methodological procedure adopted within this study.

2.2 Experimental Setups

2.2.1 RWH Setups and Rainwater Treatment System

In this study, three common roofing materials shingle (S), galvanized metal (M), clay tile (C), and three roof slopes, i.e., 5° (1), 30° (2) and 42° (3), were selected for the construction of pilot-scale roofs with a dimension of 2×2 m (Fig. 1a, b). In addition, shingle and clay tile materials are characterized by rough surface, while galvanized metal is considered as smooth. The field is at the campus urban environment, surrounded by faculty building acting as wind shields. These angles were carefully chosen to simulate the real-scale roofs in moderate climate regions that have an upper limit of 45° for roofs where below 5° roofs are classified as small angles whereas below 40° are classified as medium angles. Moreover, the most common roof angle range in moderate climate regions is 30–33°; however, for snow dominated regions, it is recommended to have 40–45° roofs. Flat roofs are mostly seen in the coastal regions. Since the location of the artificial roofs was surrounded by the buildings acting as windshields, the orientation of predominant wind did not affect the study during the rainfall events. We collected the rainwater samples from one rain event lasted ~6 h. RWH setups consisted of gutters, downpipes and polyethylene rainwater tanks with a capac-

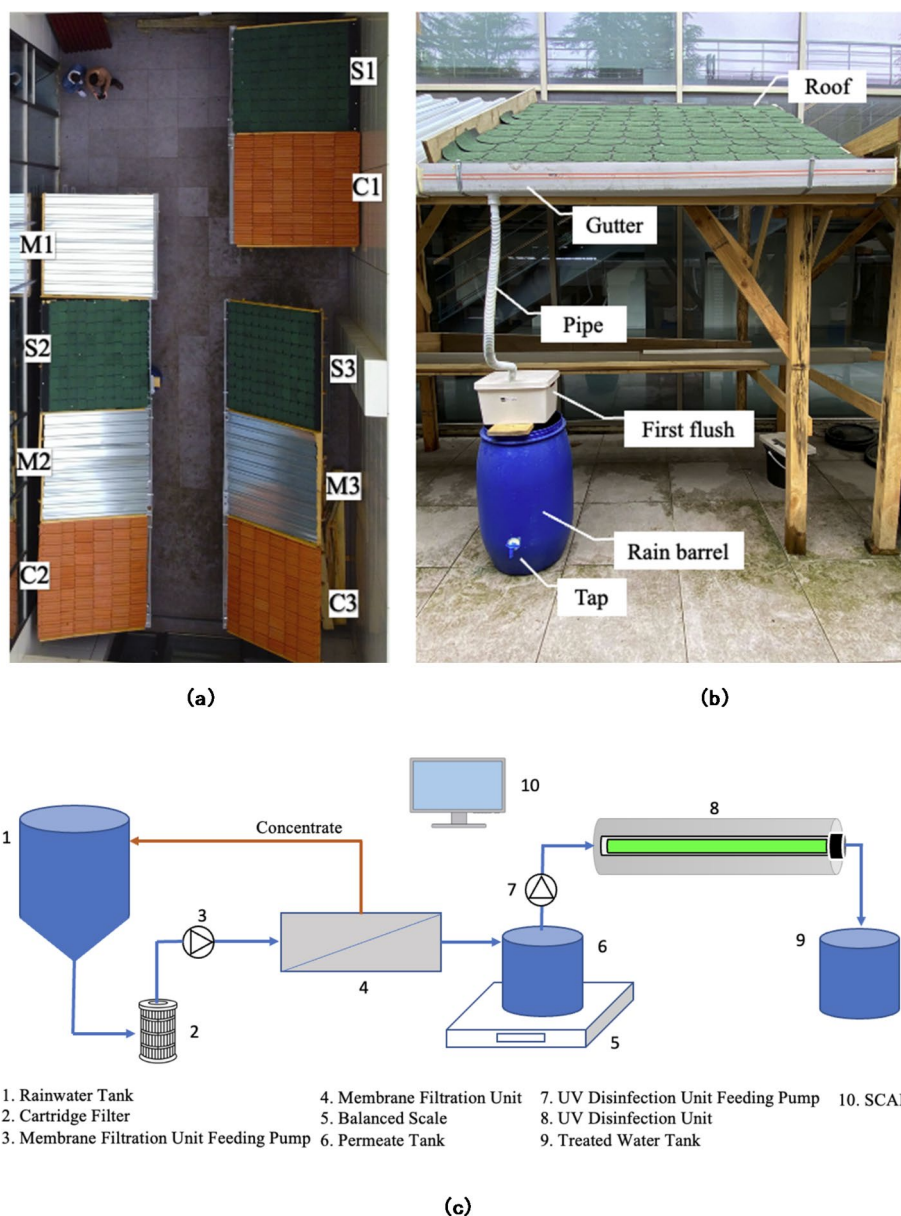


Fig. 1 RWH setups and rainwater treatment system: **a** Pilot-scale roofs, **b** RWH system components, **c** Layout of the lab-scale treatment system

ity of 100 L (Fig. 1b). Regular maintenance and cleaning of the roofs, gutters and tanks was carried out after every rain event to ensure unbiased independent experiments.

A laboratory-scale cross-flow membrane filtration system and UV disinfection unit were utilized for conducting all filtration experiments and disinfection, respectively (Fig. 1c). The filtration system comprised several essential components, namely a rainwater tank, cartridge

filter, feeding pump, membrane filtration cell, permeate tank, flow meter, pressure gauge, as well as a supervisory control and data acquisition (SCADA) software for data collection purposes. Rainwater from the feeding tank passed through a cartridge filter with a pore size of 100 μm (Aquafer, Turkey). Following the cartridge filter, the filtrate was then fed into the cross-flow system (Sterlitech SEPA, USA) membrane filtration cell, which had an effective membrane area of 140 cm^2 . A commercial flat sheet polyethersulfone (PES) UF membrane (Synder Filtration, USA) with a molecular weight cutoff (MWCO) value of 100 kDa was used. The permeate was collected in the permeate tank and its amount was measured by a balanced scale, while the concentrate was continuously recirculated to the feeding tank.

UV disinfection was conducted after membrane filtration. The UV disinfection unit (AO Smith Purfect, USA) had a working volume of 2.5 L and was fed by a peristaltic pump (Longer Pump BT100-2J, China). A flow-through cylindrical shaped chamber made of stainless steel was utilized, specifically the Purfect 06 model (USA), with a power rating of 21 watts in the UV system. The minimum and maximum operating pressures of the system were 2 bar and 10 bar, respectively. The UV light source employed was a UV-C lamp, which was equipped with a protective quartz glass covering. To achieve the minimum required dose of UV light at a wavelength of 254 nm, the experiment utilized a dosage level of 30,000 mWh/cm^2 .

2.2.2 Experimental Plan

The rainwater was harvested from pilot-scale roofs with three types of roof materials and three different slopes. The HRW from each roof after the first-flush was stored in 100-liter polyethylene rainwater tanks and taken after rain events from these tanks to determine physical, chemical, and microbiological characteristics. Afterward, the HRW from each roof was treated with a cross-flow UF membrane system and then disinfected with UV disinfection system (Fig. 2). The UF membrane system was operated at 5 bar pressure with a 90% recovery rate. For a duration of 5 min, the UV disinfection unit was utilized. The “E” letter was added to the end of the roof codes to call UF+UV system effluents (C1 represented the HRW from the clay tile roof for a 5° slope, and C1E represented the UF+UV system effluent of the harvested water).

2.3 Experimental Analyses

Chemical oxygen demand (COD), 5-day biochemical oxygen demand (BOD_5), TSS, total nitrogen (TN), total phosphorus (TP), ammonium nitrogen ($\text{NH}_4\text{-N}$), nitrate nitrogen ($\text{NO}_3\text{-N}$), sodium adsorption ratio (SAR), bicarbonate (HCO_3^-), total coliform (TC), fecal coliform (FC), *E.coli*, *Salmonella* spp. and *Legionella* spp. were measured according to Standard Methods (APHA 2017). Soluble COD (sCOD) samples were filtered through a 0.45 μm filter before the sCOD analysis. The method developed by the United States Environmental Protection Agency (US EPA) was used to quantify the helminth eggs (US EPA, 2003). Total dissolved solids (TDS) and EC parameters were measured with HQ40d Hach Portable Multimeter (Hach Company, USA). The pH of the samples was measured using a pH meter (XS Instrument, Italy). Turbidity was measured with a Hach 2100 Q Turbidimeter (Hach Company, USA), with a detection range of 0–1000 NTU. Particle size distribution (PSD) was measured by a Zetasizer Nano-S (Malvern Instruments, UK), with a detection

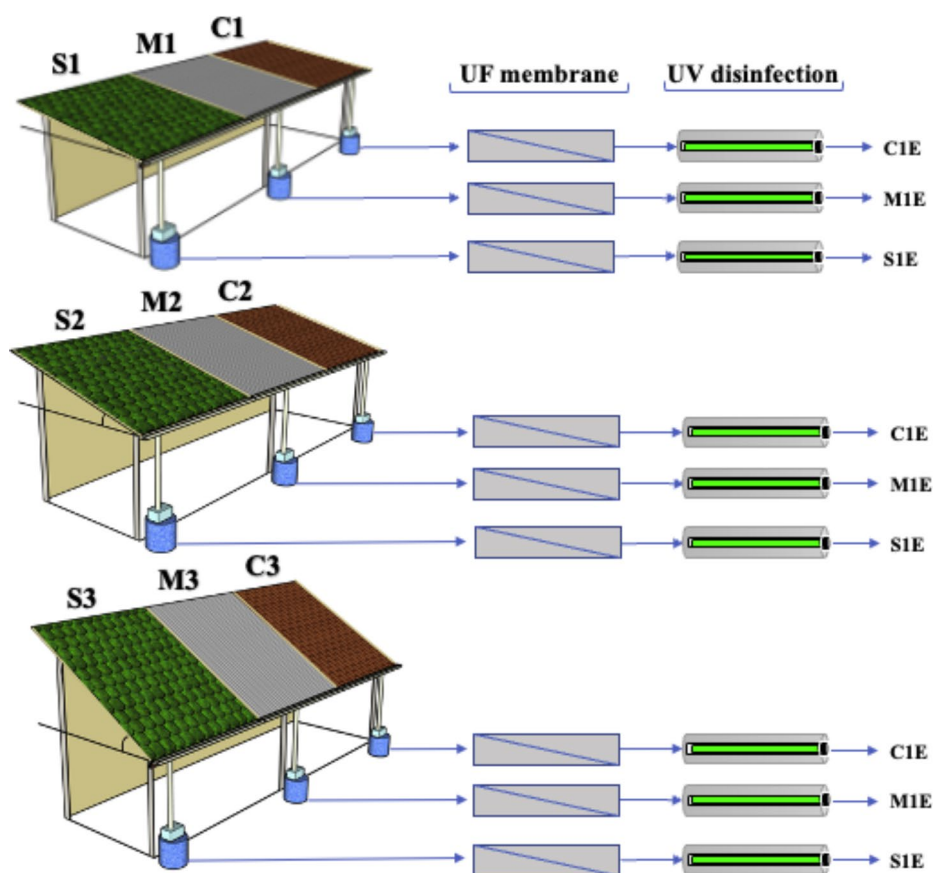


Fig. 2 RWH setups and treatment systems

range between 0.3 and 10 μm . Ions (bromide (Br^-), calcium (Ca^{2+}) chloride (Cl^-), fluoride (F^-), magnesium (Mg^{2+}), potassium (K^+), sodium (Na^+) and sulfate (SO_4^{2-}) were measured by using ion chromatography (IC, Dionex ICS-3000, USA). Heavy metals (aluminum (Al), arsenic (As), beryllium (Be), boron (B), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), iron (Fe), lead (Pb), lithium (Li), manganese (Mn), molybdenum (Mo), nickel (Ni), selenium (Se), vanadium (V) and zinc (Zn) were measured by inductively coupled plasma-optical emission spectrometry (ICP-OES, Perkin Elmer Optima 7000 DV, USA). An analysis of variance (ANOVA) was used for each parameter to test the significance of HRW collected from different roofs, with a significance level (p-value) of 0.05.

2.4 Multi Criteria Decision Making

The contemporary literature recognizes the potential of the FAHP emerging from the incorporation of fuzzy set theory into the conventional AHP proposed by Saaty (1977). Additionally, the FAHP is grounded in substituting the judgments of the experts included in the decision framework with fuzzy subsets of real numbers. The reciprocals of linguistic

variables regarding the importance degrees of the criteria were incorporated into the preferences of the experts who attended the surveys. It is also worth mentioning that, given its numerous advantages, such as simplicity, explicitness, and extensive utilization across various domains (Tavosi et al. 2024), the present research employed the triangular fuzzy membership function. In addition, the FAHP further ensures checking the consistency of the experts (Table 1) performing the pairwise comparisons. The consistency checks are achieved by calculating the consistency ratio (CR), in which CR values greater than 0.1 indicate inconsistent judgments by respondents, while lower CRs than the corresponding threshold imply a more consistent set of expert preferences. Fuzzy equivalents of linguistic expressions are determined for aggregating the group decisions. Finally, Chang's (1996) extent analysis was implemented to obtain the fuzzy quantities which are elaborated through the crisp mathematical notations.

The TOPSIS is also one of the widely utilized MCDM techniques which mainly deals with divergent alternatives to explore their prioritization (Hwang and Yoon 1981). To rank the corresponding alternatives, positive ideal solution and the negative-ideal solution are taken into account. Based on a set of predefined criteria and the evaluations made by the experts, shortest geometric distance to positive ideal solution and farthest distance to the negative ideal solution are identified. Hence, maximized benefit and minimized cost criteria are taken into account (Soto-Paz et al. 2023). Thus, the TOPSIS algorithm stands as a methodologically robust approach within the MCDM domain as it ensures systematic consideration of criteria weights and the relative proximity of alternatives to both the positive and negative ideal solutions making it widespread utilization across diverse disciplines. The TOPSIS method's versatility and rigorous analytical foundation make it a valuable tool for decision-making processes requiring a nuanced evaluation of multiple criteria.

Table 1 The details of the experts involved in the decision-making process

Expert ID	Sector	Background	Proficiency	Education Level	Experience (year)	
		Organization			Overall	In Sustainability
E1	Administerial	Ministry of Agriculture and Forestry	Environmental Engineering	MSc	8	2
E2	Academia	Faculty Member	Civil Engineering	PhD	42	31
E3	Academia	Faculty Member	Civil Engineering	PhD	24	10
E4	Academia	Faculty Member	Urban and Architectural Planning	PhD	10	3
E5	Private Sector	Producing Company	Civil Engineering	BSc	10	10
E6	Administerial	Water and Sewerage Administration	Environmental Engineering	BSc	14	9
E7	Administerial	Water and Sewerage Administration	Environmental Engineering	PhD	43	13
E8	Private Sector	Architecture and Restoration	Urban and Architectural Planning	PhD	16	16
E9	Private Sector	Contractor	Architecture	MSc	8	4
E10	Private Sector	Sub-contractor	Civil Engineering	BSc	6	6
E11	Administerial	Metropolitan Municipality	Civil Engineering	MSc	16	11
E12	Administerial	Water and Sewerage Administration	Civil Engineering	BSc	12	10

3 Results and Discussions

3.1 Experimental Studies

3.1.1 Rainwater Characterization

The characteristics of HRW from different roofing materials and different slopes are summarized in Table 2. There was no significant difference in characterization of HRW between the roofs for TN, NH₄-N and NO₃-N parameters. Concentrations of COD, sCOD, BOD₅, TSS, VSS, and TP were found to be below the measurement limits. However, HRWs from clay tile roofs had higher TDS concentration ($p < 0.05$) and EC ($p < 0.05$) compared to other roofing materials, which can be due to the nature of clay (Dondi et al. 2009).

The concentration of F⁻ ion in the HRW from clay tile roofs was higher ($p < 0.05$) in comparison to HRW from shingle and metal roofs, because clay tile roofs may contain higher fluorine-bearing compounds compared to the other roofing materials (Chipera and Bish 2002). In addition, concentrations of Ca²⁺, Na⁺, K⁺, Mg²⁺, Cl⁻ and SO₄²⁻ ions were higher ($p < 0.05$) in the HRW from clay tile roofs compared to the HRWs from other roofs. Moreover, the higher bicarbonate concentration ($p < 0.05$) of HRW from clay tile roofs may be attributed to the dissolution of calcium carbonate and magnesium carbonate compounds from the clay material (Lai et al. 2018). The concentrations of As and B were higher ($p < 0.05$) in the HRW from clay tile roofs compared to the other roofs. Lastly, the concentrations of Mn and Zn in HRW from galvanized metal roofs were considerably higher ($p < 0.05$) than those of HRW from other roof materials which may be caused by the composition of galvanized metal (Lee et al. 2012). Lower turbidity values ($p < 0.05$) in the HRW from metal roofs may be explained with fewer fractions of fine particles (Wang et al. 2018). The presence of various organic substances like leaves, dust particles, microorganisms carried by the wind, as well as bird droppings and animal feces on rooftops can lead to high levels of coliform bacteria in HRW from roofs (Tengan and Akoto 2022). FC and *E.coli* were not detected in HRW from galvanized metal roofs; however, they were found in HRW from clay tile and shingle roofs. This may be attributed to the presence of ultraviolet light from the sun and relatively higher heat absorption of the galvanized metal (Lee et al. 2012) and rough (indented) surfaces of clay tile and shingle roofs (Norman et al. 2019).

3.1.2 Treatment Performance

The effluent quality produced from integrated UF membrane and UV disinfection systems was compared with EU standards (European Commission 2020) to assess compliance with water quality class A (all food crops consumed raw where the edible part is in direct contact with reclaimed water) (Table 3). EU standards for reuse in irrigation include turbidity, BOD₅, TSS, and microbial parameters such as *E.coli*, Intestinal nematodes, *Legionella* spp. and *Salmonella* spp. (European Commission 2020). BOD₅, TSS, Intestinal nematodes, *Legionella* spp. and *Salmonella* spp. complied with the standards without the treatment for HRWs from all the roofs (Table 2). However, turbidity and *E.coli* parameters in HRW from shingle and clay tile roofs exceeded the standards. On the other hand, HRW from galvanized metal roofs met the EU standards without any treatment requirement (European Commis-

sion 2020). Mendez et al. (2011) and Meera also suggested that HRW from metal roofs often resulted in higher quality compared to HRW from shingle and metal roofs.

Combined UF and UV treatment reduced turbidity and *E.coli* parameters below the limit values of EU standards for water reuse in irrigation purposes (European Commission 2020). The turbidity parameter was reduced below 0.3 NTU in each sample after treatment with UF membrane. Also, pathogen microorganisms were not detected in the treated HRWs. These results are in line with Marszałek and Dudziak (2021) who used a combined cross-flow UF and UV treatment systems for the complete elimination of microorganisms in HRW. The results showed that the suggested treatment scheme in the study can meet the requirements of EU standards for water reuse in irrigation for HRW from shingle and clay tile roofs (European Commission 2020). Bicarbonate, Ca^{+2} and Mg^{+2} removal efficiencies were lower than 10% after the combined UF and UV treatment. Also, average removal efficiencies of TN, $\text{NH}_4\text{-N}$, $\text{NO}_3\text{-N}$, EC, TDS, Na^+ , F^+ , Cl^- , Al, B, Mn, Zn, and salinity parameters were calculated below 5% for treated rainwater.

3.2 MCDM Outcomes

3.2.1 Criteria Weighting

The MCDM approaches inherently lean on the subjective preferences of the experts, making the computation of consistency ratio (CR) is essential to ensure the reliability of criteria weighting. In this research, the experts were found as consistent within their responses based on pairwise comparison of both clusters and each criteria group. Furthermore, all the weights are computed as demonstrated in Table 4. Among main clusters, financial is the most significant dimension with a weight of 21.89%, followed by environmental (19.75%), technical (18.41%), structural (16.87%), respectively. The remaining two facets (i.e. innovation and social) are underestimated by the experts. These resultant weights corroborate the ideas of Guzmán-Sánchez et al. (2018), who suggested that economic (life cycle cost), environmental (solar power) and social (thermal insulation) issues are the three most important indicators. In addition, Table 4 shows that “operation cost” (30.96%) is the most significant criterion in terms of financial aspect in determining the optimal roof configuration. These results reflect those of Bernard and Joyfred (2020) who also identified high operational costs, price fluctuations and inadequate funds as the factors that can delay or cancel the deployment RWH system to harvest and save water. “*E.coli* content” was found as the most influential criterion in the selection of optimal roof configuration for agricultural irrigation purposes. Morgado et al. (2022) detected *E.coli* in some HRW samples, however; the concentrations measured from their rooftop waters fell far below current Good Agricultural Practices (GAP) food safety guidelines for irrigation water. Despite 2nd position of the environmental cluster, the superiority of the “*E.coli* content” over other environmental criteria emphasized its role in the general assessments. A similar conclusion can also be made for the “reduced runoff” criterion which ranked 3rd with a global weight of 5.73%. Given the highest weight of the financial criteria, the important role of the “operational cost” and “investment cost” was put forward, and they positioned at 2nd and 4th place in the global evaluation (Table 4). As expected due to their cluster weights, most of the social- and innovation-related factors manifested relatively lower effects regarding the topic of interest.

Table 2 Harvested rainwater (HRW) characterization

Parameter	Unit	Value (Average±Standard Deviation)								
		S1	S2	S3	M1	M2	M3	C1	C2	C3
<i>Physical Parameters</i>										
pH	-	6.76±0.10	6.68±0.10	6.77±0.09	6.59±0.08	6.59±0.09	6.57±0.08	6.81±0.20	6.81±0.14	6.78±0.20
Turbidity	NTU	7.61±0.80	6.91±0.25	5.72±0.39	3.83±0.26	4.34±0.58	3.40±0.52	5.11±0.69	6.59±0.59	5.39±0.52
D50 ^a	nm	92.5±168	832±85	887±125	1133±125	1108±154	1164±117	1076±72	960±93	1066±98
<i>Chemical Parameters</i>										
BOD ₅	mg/L	<10	<10	<10	<10	<10	<10	<10	<10	<10
COD	mg/L	<40	<40	<40	<40	<40	<40	<40	<40	<40
sCOD	mg/L	<40	<40	<40	<40	<40	<40	<40	<40	<40
TSS	mg/L	<10	<10	<10	<10	<10	<10	<10	<10	<10
VSS	mg/L	<10	<10	<10	<10	<10	<10	<10	<10	<10
TN	mg/L	2.05±0.46	2.11±0.40	1.60±0.27	1.60±0.37	2.21±0.37	1.80±0.36	1.86±0.43	1.76±0.41	1.82±0.29
NH ₄ -N	mg/L	0.29±0.03	0.30±0.02	0.30±0.02	0.27±0.01	0.27±0.04	0.28±0.04	0.30±0.02	0.29±0.02	0.26±0.02
NO ₃ -N	mg/L	0.83±0.05	0.80±0.05	0.76±0.05	0.81±0.03	0.84±0.06	0.70±0.06	0.84±0.08	0.81±0.03	0.74±0.05
TP	mg/L	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
EC	μS/cm	40.0±4.9	34.4±6.4	37.1±5.1	24.8±7.7	23.3±4.5	25.2±6.3	52.9±8.7	47.6±5.5	45.3±8.4
TDS	mg/L	17.5±2.4	16.6±2.9	17.1±1.9	11.3±3.1	10.4±2.2	11.9±3.4	23.4±4.3	21.8±2.4	21.3±3.1
Salinity	psu ^b	0.26±0.06	0.02±0.01	0.02±0.01	0.25±0.06	0.02±0.01	0.02±0.01	0.03±0.01	0.03±0.01	0.03±0.01
Bicarbonate	mg/L	62.5±9.0	53.3±9.0	58.3±6.2	50.0±8.7	45.8±7.3	48.3±7.5	75.8±5.3	75.0±9.6	69.2±10.2
Ca ²⁺	mg/L	5.42±0.61	4.39±0.63	4.07±0.79	2.86±0.69	3.82±0.28	2.11±0.29	6.33±5.55	5.74±0.71	6.52±0.99
K ⁺	mg/L	0.25±0.04	0.25±0.06	0.27±0.06	0.23±0.08	0.18±0.04	0.24±0.07	0.37±0.06	0.35±0.06	0.32±0.07
Mg ²⁺	mg/L	0.28±0.05	0.23±0.04	0.25±0.05	0.26±0.05	0.19±0.04	0.11±0.02	1.28±0.17	1.74±0.21	1.52±0.29
Na ⁺	mg/L	1.62±0.31	1.03±0.28	0.92±0.25	1.15±0.31	0.82±0.14	0.81±0.19	2.00±0.45	1.41±0.27	1.74±0.23
Cl ⁻	mg/L	0.76±0.09	0.79±0.14	0.79±0.10	0.70±0.12	0.72±0.16	0.74±0.11	0.88±0.08	0.94±0.13	1.06±0.11
F ⁻	mg/L	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	0.14±0.02	0.17±0.02	0.28±0.05
SO ₄ ²⁻	mg/L	2.21±0.22	1.88±0.30	2.19±0.35	2.06±0.26	1.96±0.26	2.31±0.24	5.07±0.70	6.14±0.71	4.52±0.76
<i>Heavy Metals</i>										

Table 2 (continued)

Parameter	Unit	Value (Average±Standard Deviation)									
		S1	S2	S3	M1	M2	M3	C1	C2	C3	
Al	µg/L	<25	<25	<25	<25	<25	<25	<25	<25	<25	
As	µg/L	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	1.0±0.2	1.2±0.3	1.1±0.2	
B	mg/L	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	0.060±0.010	0.071±0.013	0.061±0.012	
Be	µg/L	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	
Cd	µg/L	<10	<10	<10	<10	<10	<10	<10	<10	<10	
Cr	µg/L	<25	<25	<25	<25	<25	<25	<25	<25	<25	
Co	µg/L	<25	<25	<25	<25	<25	<25	<25	<25	<25	
Cu	µg/L	<25	<25	<25	<25	<25	<25	<25	<25	<25	
Fe	µg/L	<10	<10	<10	<10	<10	<10	<10	<10	<10	
Pb	µg/L	<25	<25	<25	<25	<25	<25	<25	<25	<25	
Li	µg/L	<25	<25	<25	<25	<25	<25	<25	<25	<25	
Mn	µg/L	<10	<10	<10	12.91±0.96	13.99±1.16	17.30±2.27	<10	<10	<10	
Mo	µg/L	<10	<10	<10	<10	<10	<10	<10	<10	<10	
Ni	µg/L	<25	<25	<25	<25	<25	<25	<25	<25	<25	
Se	µg/L	<10	<10	<10	<10	<10	<10	<10	<10	<10	
V	µg/L	<25	<25	<25	<25	<25	<25	<25	<25	<25	
Zn	µg/L	<25	<25	<25	1758±157	1604±167	1800±129	<25	<25	<25	
Microbiological Parameters											
TTC	cfu ^c /100 mL	958±112	1052±199	879±97	307±63	265±39	135±41	828±85	873±171	742±65	
FC	cfu/100 mL	73±26	135±39	113±30	n.d. ^d	n.d.	n.d.	58±18	75±24	62±23	
E.coli	cfu/100 mL	48±15	52±12	53±14	n.d.	n.d.	n.d.	38±7	45±15	47±17	
Intestinal nematodes (helminth eggs)	egg/L	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	

Table 2 (continued)

Parameter	Unit	Value (Average $\pm$ Standard Deviation)								
		S1	S2	S3	M1	M2	M3	C1	C2	C3
<i>Legionella</i> spp.	cfu/L	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
<i>Salmonella</i> spp.	cfu/L	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

^aD50: Median particle size^bpsu: Practical salinity unit^ccfu: Colony forming unit^dn.d.: Not detected

Table 3 Comparison of the quality of treated rainwater with EU standards for water reuse in irrigation

Parameter	Unit	Value (Average ± Standard Deviation)								Standards ^a			
		S1E	S2E	S3E	M1E	M2E	M3E	C1E	C2E	C3E	Value	CS ^b	
Physical Parameters													
pH	-	6.76±0.04	6.73±0.10	6.71±0.06	6.63±0.03	6.62±0.05	6.65±0.05	6.85±0.02	6.83±0.10	6.81±0.08	-	-	
Turbidity	NTU	0.25±0.02	0.23±0.03	0.22±0.03	0.19±0.03	0.20±0.03	0.19±0.02	0.24±0.02	0.23±0.02	0.23±0.03	≤5	✓	
D50	nm	222±65	251±102	223±54	305±147	342±80	387±95	241±50	285±77	335±84	-	-	
Chemical Parameters													
BOD ₅	mg/L	<10	<10	<10	<10	<10	<10	<10	<10	<10	≤10	✓	
COD	mg/L	<40	<40	<40	<40	<40	<40	<40	<40	<40	-	-	
sCOD	mg/L	<40	<40	<40	<40	<40	<40	<40	<40	<40	-	-	
TSS	mg/L	<10	<10	<10	<10	<10	<10	<10	<10	<10	≤10	✓	
VSS	mg/L	<10	<10	<10	<10	<10	<10	<10	<10	<10	-	-	
TN	mg/L	1.96±0.44	2.03±0.39	1.53±0.26	1.53±0.35	2.13±0.35	1.72±0.35	1.78±0.40	1.68±0.40	1.74±0.28	-	-	
NH ₄ -N	mg/L	0.28±0.03	0.30±0.03	0.29±0.03	0.27±0.02	0.88±0.17	0.28±0.04	0.29±0.03	0.28±0.03	0.26±0.02	-	-	
NO ₃ -N	mg/L	0.82±0.06	0.78±0.06	0.74±0.06	0.80±0.03	0.82±0.06	0.69±0.06	0.82±0.09	0.80±0.03	0.73±0.05	-	-	
TP	mg/L	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	-	-	
EC	µS/cm	38.9±4.8	33.3±6.3	35.8±5.0	24.1±7.5	22.5±4.4	24.3±6.2	51.2±8.4	46.1±5.4	43.9±8.1	-	-	
TDS	mg/L	16.8±2.2	15.8±3.0	16.3±1.9	10.8±3.0	10.0±2.1	11.4±3.3	22.5±4.1	20.9±2.3	20.4±3.0	-	-	
Salinity	psu	0.26±0.06	0.02±0.01	0.02±0.01	0.25±0.06	0.02±0.01	0.02±0.01	0.03±0.01	0.03±0.01	0.03±0.01	≤10	-	
Bicarbonate	mg/L	58.8±8.6	49.9±8.0	54.7±5.9	47.0±8.4	42.8±7.1	45.5±7.0	71.1±4.7	70.5±9.2	65.3±9.7	-	-	
Ca ²⁺	mg/L	5.04±0.58	4.08±0.60	3.78±0.75	2.66±0.65	3.55±0.27	1.96±0.27	5.88±0.52	5.34±0.66	6.06±0.93	-	-	
K ⁺	mg/L	0.25±0.04	0.25±0.06	0.27±0.07	0.23±0.08	0.18±0.04	0.23±0.07	0.36±0.06	0.35±0.06	0.31±0.07	-	-	
Mg ²⁺	mg/L	0.26±0.05	0.22±0.04	0.23±0.05	0.24±0.05	0.18±0.04	0.11±0.02	1.18±0.16	1.60±0.66	1.40±0.27	-	-	
Na ⁺	mg/L	1.57±0.30	1.00±0.27	0.90±0.24	1.11±0.30	0.80±0.13	0.78±0.19	1.94±0.43	1.37±0.26	1.68±0.22	-	-	
Cl ⁻	mg/L	0.74±0.09	0.78±0.14	0.77±0.10	0.68±0.12	0.71±0.15	0.72±0.11	0.86±0.08	0.93±0.13	1.04±0.11	-	-	
F ⁻	mg/L	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	0.14±0.02	0.18±0.02	0.28±0.06	-	-	
SO ₄ ²⁻	mg/L	1.71±0.29	1.69±0.16	1.66±0.25	2.14±0.31	1.89±0.26	2.53±0.40	4.88±0.68	5.90±0.68	4.35±0.74	-	-	
Heavy Metals													
Al	µg/L	<25	<25	<25	<25	<25	<25	<25	<25	<25	-	-	
As	µg/L	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	0.98±0.1	1.17±0.2	1.07±0.1	-	-	
B	mg/L	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	0.059±0.011	0.069±0.012	0.060±0.012	-	-	
Be	µg/L	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	-	-	

Table 3 (continued)

Parameter	Unit	Value (Average ± Standard Deviation)										Standards ^a	
		S1E	S2E	S3E	M1E	M2E	M3E	C1E	C2E	C3E	Value	CS ^b	
Cd	µg/L	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	-	-
Cr	µg/L	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	-	-
Co	µg/L	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	-	-
Cu	µg/L	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	-	-
Fe	µg/L	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	-	-
Pb	µg/L	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	-	-
Li	µg/L	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	-	-
Mn	µg/L	<10	<10	<10	12.80±1.05	13.68±2.05	16.80±1.88	<10	<10	<10	<10	-	-
Mo	µg/L	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	-	-
Ni	µg/L	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	-	-
Se	µg/L	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	-	-
V	µg/L	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	-	-
Zn	µg/L	<10	<10	<10	1726±131	1604±123	1759±137	<10	<10	<10	<10	-	-
<i>Microbiological Parameters</i>													
TC	cfu/100 mL	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	-	-
FC	cfu/100 mL	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	-	-
<i>E.coli</i>	cfu/100 mL	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	≤10	✓
Intestinal nematodes (helminth eggs)	egg/L	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	<1	✓
<i>Legionella</i> spp.:	cfu/L	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	<1,000	✓
<i>Salmonella</i> spp.	cfu/L	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0	✓

^aStandards: European Union Standards (European Commission 2020)

^bCS: Compliance with standards

✓: Compliance

Table 4 Global weights and corresponding rankings of the decision criteria

Main Cluster	Cluster Weight	ID	Criteria	Local Weights	Global Weights	Global Ranking
Financial	0.2189	FN1	Investment Cost	0.2601	0.0569	4
		FN2	Operational Cost	0.3096	0.0678	2
		FN3	Governmental Incentives	0.1856	0.0406	12
		FN4	Use of Local Resources	0.2447	0.0536	6
Structural	0.1687	ST1	Structural Load	0.3142	0.0530	7
		ST2	Risk of Failure	0.1644	0.0277	22
		ST3	Fire Risk	0.2790	0.0471	10
		ST4	Wind Resistance	0.2423	0.0409	11
Technical	0.1841	TC1	Construction Complexity	0.2945	0.0542	5
		TC2	Ease of Maintenance	0.2842	0.0523	8
		TC3	Recyclability	0.1592	0.0293	21
		TC4	Insulation Capacity	0.2620	0.0482	9
Environmental	0.1975	EN1	Reduced Runoff	0.2900	0.0573	3
		EN2	Turbidity	0.1583	0.0313	16
		EN3	<i>E.coli</i> Content	0.3546	0.0700	1
		EN4	Mitigating UHI	0.1972	0.0390	13
Social	0.1147	SO1	Client Interest	0.1676	0.0192	24
		SO2	Compliance with R&S	0.2606	0.0299	20
		SO3	Suitability for Region	0.2859	0.0328	14
		SO4	Aesthetic Appearance	0.2859	0.0328	14
Innovation	0.1160	IN 1	Use of Innovative Materials	0.2591	0.0301	17
		IN 2	Adaptability of Modular Construction Technologies	0.2579	0.0299	19
		IN 3	Adaptation of Digital Technologies	0.2239	0.0260	23
		IN 4	Adaptation of Energy-Efficient Techniques	0.2591	0.0301	17

Table 5 Finalized prioritization of the roof alternatives

$d+$	$d-$	CC_i	Rank	Alternative Roof Formations
1.19E-03	4.91E-04	0.2914	4	S1
1.28E-03	4.11E-04	0.2426	6	S2
1.35E-03	3.29E-04	0.1965	7	S3
2.20E-04	1.50E-03	0.8724	1	M1
2.33E-04	1.41E-03	0.8584	2	M2
2.89E-04	1.34E-03	0.8229	3	M3
9.56E-04	3.12E-04	0.2457	5	C1
1.17E-03	2.47E-04	0.1748	8	C2
1.32E-03	2.17E-04	0.1412	9	C3

3.2.2 Alternative Prioritization

This study subjected nine different roof configurations to the overall assessments in order to find the most appropriate alternative for agricultural irrigation purposes. Hence, concerning the entirety of dimensions, CC_i values were computed and the alternatives are ranked with respect to the corresponding closeness coefficients in Table 5. Regardless of the roof

slopes, galvanized metal material is the most appropriate selection for agricultural irrigation purposes. Among different slope alternatives of the galvanized metal material, this research found the roof configuration containing the use of galvanized metal with 5° of slope as the most feasible alternative as it has the highest CC_i value: 0.8724. Also, it is worth mentioning that, with slight differences in closeness coefficients, galvanized metal with 30° and 42° slopes are ranked 2nd (0.8584) and 3rd (0.8229), respectively. According to material-basis evaluations made, shingle material can be acknowledged as the 2nd most appropriate material given the agricultural irrigation purposes within a circularity concept. In this regard, shingle roofs with 5°, 30° and 42° slopes are positioned on 4th, 6th, and 7th, respectively. It is worth mentioning that, even though clay tile with a slope of 5° yielded a greater closeness coefficient than shingle roofs with 30° and 42° slopes, this can be considered a subtle distinction, especially for the shingle with a 30° slope. However, despite the least effectiveness of the clay tiles, having 5° of slope makes the relevant alternatives an advantageous choice compared to other degree slopes. This can be attributed to the construction complexity (5th most important criterion in global weight assessments) of higher degree roofs.

In terms of environmental considerations, the production of clay tile roofs significantly contributes to global warming potential, particularly due to the energy-intensive firing process (Fernando and Karunaratne 2023). Galvanized metal roofs, on the other hand, have high recycling potential, which can reduce carbon emissions by 73% compared to producing through mining and processing (Le et al. 2018). While shingle roofs are more cost-effective than metal roofs; they have a higher environmental burden due to frequent maintenance and shorter lifespan. Asphalt-based shingle roofs, in particular, are less sustainable long-term (Zhang et al. 2014). Life cycle analysis shows that asphalt shingle roofs tend to have higher environmental impacts in terms of energy use and waste generation, especially considering the need for frequent maintenance and replacement (Fernando and Karunaratne 2023).

It is encouraging to compare the rankings in Table 5 with that found by Sackey and Kim (2018) who recommended asphalt shingles to be a cost-effective, environmentally friendly roofing material compared to clay tiles when balancing the environmental performance against the economic performance. In the same study, clay tile had a better environmental performance score, compared to the score of asphalt shingles; however, asphalt shingles had a better overall performance.

Following the present results, previous studies have demonstrated that differences in runoff water quality vary between sloping smooth and flat rough roofs. Farreny et al. (2011) found that the flat gravel roof contained higher levels of all pollutants (except for NH_4) due to particle accumulation, roof weathering and plants. Not surprisingly, sloping roofs (such as clay tile and metal) present better quality. The findings of this study broadly support the work of other studies in the RWH field linking steel roofs with higher quality as compared to asphalt shingle roofs (Despins et al. 2009). In another study, Mendez et al. (2011) showed that rainwater from metal roofs has mostly the lowest concentrations of microorganisms.

4 Conclusion

Harvesting rainwater has become a crucial issue as it helps mitigate water scarcity and alleviate pressure on existing water resources in sustainable world. In this study, rainwater samples from nine pilot-scale rooftops were characterized in order to determine the differ-

ences in quality. Lower turbidity values and *E.coli* concentrations were found in the rainwater from the galvanized metal roof which met the EU standards for water reuse in irrigation. However, turbidity and *E.coli* parameters were found higher in the rainwater from shingle and clay tile roofs in comparison to EU standards. Therefore, rainwater from shingle and clay tile roofs was treated with a sequential UF membrane and UV disinfection system, resulting in treated water that met the EU standards for irrigation. The criteria weighting outcomes indicated that the financial aspect was the most important dimension for assessing agricultural irrigation purposes with rainwater harvesting attempts. Among several criteria, *E.coli* content was found as the most influential parameter, followed by the operational cost, reduced runoff, investment cost, and construction complexity. In the comparison of roof materials, galvanized metal material outperformed its counterparts (namely shingle and clay tiles) by demonstrating satisfactory performance with respect to the environmental, technical, and structural aspects. From an environmental perspective, monitoring changes in HRW quality over the long term is essential to investigate roof material leaching over time. Additionally, future studies should investigate HRW quality across various roofing materials, such as green roofs, ondulin, concrete, and plastic.

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Data Availability The authors declare that the data supporting the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Ethical Approval This declaration is not applicable.

Consent to Participate This declaration is not applicable.

Consent of Publish This declaration is not applicable.

Competing Interests The authors declare no competing interests.

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