Prioritizing Sustainable Water Technologies in Morocco Through a Tetralemma Decision Support Framework

Muhammad Ikram[a1], Cosimo Magazzino[bcd], Ernesto D.R. Santibanez Gonzalez[e]

[a]*School of Business Administration (SBA), Al Akhawayn University in Ifrane, Avenue Hassan II, P.O. Box 104, 53000 Ifrane, Morocco*

[b]*Economic Research Center, Western Caspian University, Baku, Azerbaijan*

[c]*ARUCAD Research Centre, Arkin University of Creative Arts and Design, Kyrenia, Northern Cyprus, Turkey*

[d]*Department of Management, Finance and Technology, LUM University "Giuseppe Degennaro", Casamassima, Italy*

[e]*CES4.0 and Industrial Engineering Department, Faculty of Engineering, University of Talca, Los Niches Km. 1, Curico, Chile*

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Abstract

This study develops a tetralemma decision support framework for prioritizing sustainable water technologies in Morocco under uncertainty. Seven technologies were assessed against 16 criteria spanning water security, equity, sustainability, and governance. An integrated fuzzy Trial and Evaluation Laboratory (DEMATEL), Analytic Network Process (ANP) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) approach modeled experts' judgements and interdependencies. Results reveal that governance received the greatest weight (28.5%), followed by equity (25%), security (24.4%), and sustainability (22.1%). Anaerobic Membrane Bioreactor (AnMBR, T3) ranked highest, reflecting strong performance in technical, socio-economic, and environmental aspects. The framework supports transparent comparison of technology alternatives and guiding strategic investments and policy decisions toward sustainable water futures.

Keywords: Water resilience; water security; sustainable water technologies; sustainable development; climate change; integrated decision support.

1. Introduction

[1] Corresponding Author: Muhammad Ikram, i.muhammad@aui.ma.

Water insecurity threatens ecosystems, economies, and human well-being. The World Economic Forum identifies water crises (WEF, 2020), while approximately four billion people experience severe water insecurity for at least one month annually (du Plessis, 2023). Population growth, urbanization, and irrigated agriculture increase demand as climate change intensifies hydrological variability and drought (El Kenawy, 2024). These pressures are particularly acute in arid and semi-arid countries such as Morocco.

Morocco's drought in February 2024 illustrates these pressures. Figure 1 shows reduced vegetation and soil moisture compared with February 2023 (NASA, 2024). Reservoir depletion constrained irrigation and crop production; Al Massira Dam reportedly fell 1-2% in capacity (United Nations Educational, 2024). By mid-February 2024, reservoirs nationwide were at only 25% capacity, promoting restrictions on non-essential urban water use and highlighting the risks to food security and agricultural livelihoods. Population growth, urbanization, and intensive irrigation agriculture compound the pressure on freshwater resources (Kaczmarek et al., 2023).

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Figure 1: NASA satellite images capture drought parches in Morocco (NASA, 2024)

Morocco's annual freshwater availability per capita declined from approximately 2,500-2,600 m^3 to an estimated 600-650 m^3 below the water poverty threshold of 1000 m^3 (El Khalki et al., 2021). Chronic shortages contribute to aquifer overexploitation, competition among agricultural, urban, and industrial users, and food insecurity during droughts (Karmaoui et al., 2022). These conditions make water security a persistent constraint on national development.

Traditional engineering responses alone are insufficient to secure Morocco's water supply (Guemouria et al., 2023). A resilience-oriented strategy must combine infrastructure, demand management, and technological innovation. Policies promoting conservation, pricing, and allocation mechanisms should accompany efforts to diversify supply (Silva-Novoa Sánchez et al., 2022). Technology investments include irrigation upgrades, distribution-loss reduction desalination and

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wastewater reuse. Recent programs emphasize desalination and treatment for reuse, including projects serving the Casablanca region and agricultural and industrial users (UM6P, 2024). These options can reduce or expand supply, but their costs, energy requirements, and governance demand differ. Decision-makers therefore need a systematic basis for comparing benefits and trade-offs under Morocco's resources and institutional constraints.

This study evaluates and prioritizes sustainable technologies through an integrated water resilience tetralemma comprising Water Security (WS), Water Equity (WE), Environmental Sustainability (ES), and Water Governance & Management (WGM). The hybrid multi-criteria decision-making (MCDM) approach combines Fuzzy DEMATEL, Fuzzy ANP, and Fuzzy TOPSIS to address interdependencies and uncertainty in expert judgments. The framework's contribution is to assess the four dimensions jointly, linking technical performance to social, environmental, and governance considerations within a single decision model. Its objective is to identify technologies that offer the most favorable balance across the four dimensions for Morocco and provide a transparent basis for strategic investment. The approach also offers a transferable structure for water resource decisions that require multiple, potentially competing priorities to be considered together.

2. Proposed Integrated Decision Support Framework

The proposed decision-support framework assesses sustainable water technologies using criteria grounded in the water tetralemma. It comprises four stages, illustrated in Figure 2. A literature survey established a criteria-based framework for each dimension of the water security tetralemma, and expert opinions were solicited to finalize the criteria. Sustainable water technology alternatives were evaluated for their applicability in the Moroccan context.

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The framework applies a hybrid fuzzy MCDM, combining fuzzy DEMATEL, fuzzy ANP, and fuzzy TOPSIS, to rank technologies across water availability, economic cost-effectiveness, environmental impact, and social/governance considerations. Integrating expert knowledge and addressing uncertainty through fuzzy logic provides a structured, transparent basis for identifying technologies with the greatest benefits. The computational steps are as follows: Fuzzy DEMATEL determines the internal dependencies among the water tetralemma dimensions and their associated criteria. Subsequently, fuzzy ANP identifies external relationships among criteria and calculates their weights. Fuzzy TOPSIS then uses these weights to rank the alternatives.

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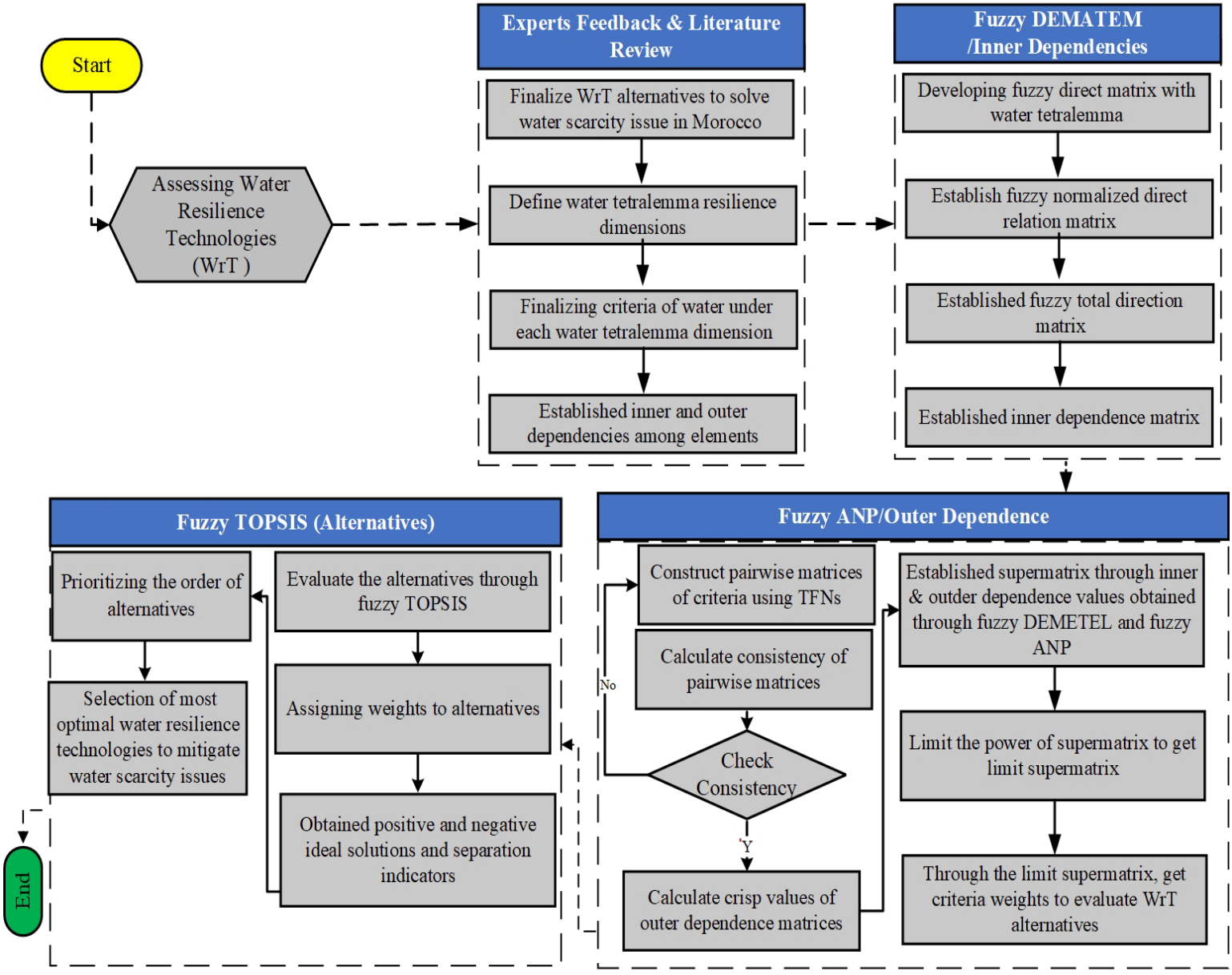


Figure 2: A schematic integrated methodological framework operationalized in this study.

2.1 Evaluation of Sustainable Water Technology Alternatives

Water treatment technologies fall into three main categories: membrane-based, biological-based, and chemical/adsorptive (Figure 3). Membrane methods include reverse osmosis, forward osmosis, and electrodialysis; biological treatments include anaerobic membrane bioreactors and constructed wetlands; and chemical/adsorptive methods include advanced oxidation processes and

biochar filtration. Figure 3 groups these alternatives and highlights key characteristics of each category, providing context for their evaluation in this study.

Membrane-based processes, including reverse osmosis (RO), forward osmosis (FO), and electrodialysis (ED/EDR), use semi-permeable membranes to physically separate contaminants. They typically yield high-quality water but require considerable energy input through pressure or electrical potential (Shehata et al., 2023). Biologically based technologies, including anaerobic membrane bioreactors (AnMBRs) and constructed wetlands, use microbial activity or natural ecosystems for water treatment and resource recovery. They generally require less energy and offer biogas production or habitat creation, although larger spatial footprints or meticulous management may be necessary (Shurair et al., 2019). Chemical and adsorptive methods, including advanced oxidation processes and biochar filtration, utilize reactions, such as oxidation, or sorbent materials to eliminate or degrade pollutants (Shrestha et al., 2021). These approaches target persistent contaminants and improve water quality; however, they require chemical reagents or produce residual byproducts. The following subsections outline these technologies.

2.1.1 Membrane Technologies

Reverse osmosis uses pressure to push water through a semipermeable membrane, removing dissolved salts and impurities (Boussouga et al., 2021). It is among the most common desalination and water treatment methods worldwide, accounting for about 60% of desalination capacity. By producing high-quality drinking water from seawater, brackish water, or wastewater, reverse osmosis provides an important option for areas facing water security challenges.

In forward osmosis, a concentrated draw solution extracts water across a membrane from a dilute feed, such as wastewater or saline water, without the significant applied pressure required by reverse osmosis (Dsilva Winfred Rufuss et al., 2022). Lower pressure reduces susceptibility to

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fouling and scaling, lowering cleaning needs and potentially extending membrane lifespan. Applications include wastewater concentration, energy-efficient desalination hybrids, and reuse, particularly where high salinity or difficult feed waters reduce reverse osmosis efficiency (Karunakaran et al., 2021). A secondary process, such as reverse osmosis or thermal separation, is typically required and may offset forward osmosis energy savings (Abdul-Hussein et al., 2024).

Electrodialysis (ED/EDR) separates ions using selective ion-exchange membranes. This membrane-based desalination technique uses an electric potential to drive salt ions through the membranes, demineralizing the feed water (Jashni & Hosseini, 2022). Traditional electrodialysis places cation and anion exchange membranes alternately between electrodes. EDR reverses electrode polarity at regular intervals to reduce membrane fouling and scaling (Easley et al., 2023). Advantages include generally high water recovery and tolerance to scaling species (Kaniadakis et al., 2024). Energy use depends more closely on the water's ionic content than on the total volume processed. Consequently, ED/EDR is more energy-efficient for lower salinity applications, where it can cost less than reverse osmosis (He et al., 2024).

2.1.2 Biological Technologies

Anaerobic Membrane Bioreactors (AnMBRs) combine anaerobic biological treatment with membrane filtration. An AnMBR uses an oxygen-free bioreactor for wastewater treatment, where anaerobic microorganisms decompose organic pollutants and produce biogas (methane) as a valuable byproduct (Lee & Liao, 2021). A membrane, typically microfiltration or ultrafiltration, filters treated water within the reactor or an external loop while retaining biomass in the system. Separating hydraulic retention time (the time water remains in the reactor) from solids retention time (the time biomass remains in the reactor) enables longer retention of microorganisms and sludge, improving organic conversion and effluent quality (Yu et al., 2024). AnMBRs effectively treat

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high-strength wastewater from sources such as industry and agriculture, achieving significant organic matter removal and producing renewable energy as biogas.

Advances in membrane materials, fouling control methods through scouring and gas sparging, and reactor design aim to improve AnMBR reliability. By combining water treatment, waste sludge reduction, and energy recovery, AnMBRs have the potential to provide sustainable treatment that supports water resilience and resource recovery (Zhang et al., 2021).

Constructed Wetlands (CWs) are engineered wastewater treatment systems using wetland vegetation, soils, and microbial communities. Within a controlled environment, they replicate natural wetland pollutant-removal processes, including sedimentation, filtration, plant uptake, and microbial degradation (Kataki et al., 2021).

CWs provide a green, energy-efficient means of wastewater treatment (Younas et al., 2022), with applications in municipal sewage, agricultural runoff, industrial effluents, and acid mine drainage. Advantages include operational simplicity, low operation and maintenance costs, habitat creation, and management of intermittent flows (Deng et al., 2021). When well designed and maintained, constructed wetlands can remove organic matter, nutrients, pathogens, and metals, potentially providing resilient treatment consistent with environmental principles (Gonzalez-Flo et al., 2023).

2.1.3 Chemical and Adsorptive Technologies

Advanced Oxidation Processes (AOPs) generate highly reactive oxidizing species, particularly hydroxyl radicals (OH), to degrade organic pollutants in water (Babu Ponnusami et al., 2023). These chemical treatments oxidatively degrade persistent organic contaminants, including pharmaceuticals, endocrine disruptors, pesticides, and other micropollutants that typically resist conventional water treatment (Chen et al., 2021).

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AOPs frequently serve as a final treatment step to improve water quality or minimize specific contaminants (Titchou et al., 2021). In wastewater reclamation, they degrade contaminants remaining after biological treatment to meet potable reuse standards. Their effectiveness entails trade-offs; chemical inputs, such as ozone and hydrogen peroxide, or energy for UV lamps or catalysts can increase costs (Sun et al., 2023).

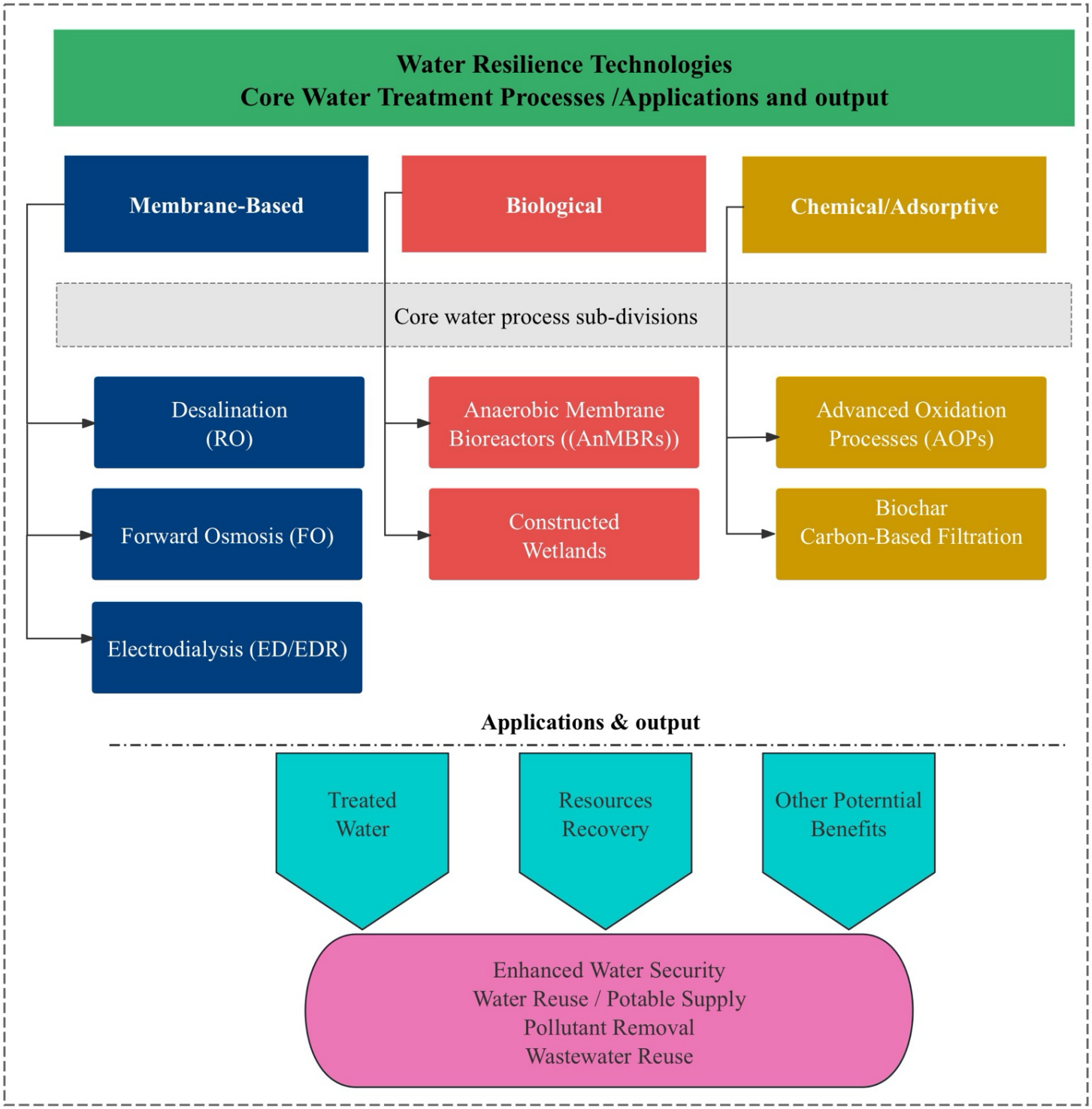
Biochar is a carbon-based filtration medium and adsorbent produced by pyrolysis. This carbon-rich, porous material has a large surface area and numerous functional groups (Soffian et al., 2022). Research identifies biochar as an efficient, sustainable option for removing contaminants, including heavy metals and organic compounds, from water and wastewater (Priya et al., 2024; Gupta et al., 2022). Water passes through a biochar bed, where pollutants adsorb onto the char surface or become trapped in its pores (Moureen et al., 2024). Biochar can adsorb lead, arsenic, and copper through ion exchange or surface complexation (Kang et al., 2022).

Biochar can be produced locally from waste biomass, aligning with resource recovery principles and contributing to climate change mitigation through carbon sequestration (Kang et al., 2022). It is a more affordable alternative to conventional activated carbon filters, making water filtration more accessible for people in rural or resource-limited areas. After use, biochar containing contaminants requires appropriate handling or regeneration; it may serve as a soil amendment

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179 if contaminants are immobilized, or it can be re-pyrolyzed to eliminate organic materials (Laghari

180 et al., 2021).



181 **Figure 3:** Classification of sustainable water technologies, along with applications and output.

2.2 Establishing Tetralemma Water Resilience Criteria

Four key dimensions underpin sustainable water management and the evaluation of technology alternatives: water security, water equity, environmental sustainability, and water governance & management. The study aims to develop resilient water systems that balance reliable, sufficient resources; equitable distribution; environmental harmony; and effective management through robust institutions. These dimensions and their sub-criteria provide the foundation for assessing sustainable water technology. Figure 4 illustrates the tetralemma's dimensions and their assessment criteria. Each quadrant represents one dimension, Water Security (WS), Water Equity (WE), Environmental Sustainability (ES), and Water Governance & Management (WGM), and lists its evaluation criteria. This figure shows the breadth and organization of assessment, while the following subsections describe each dimension and sub-criteria.

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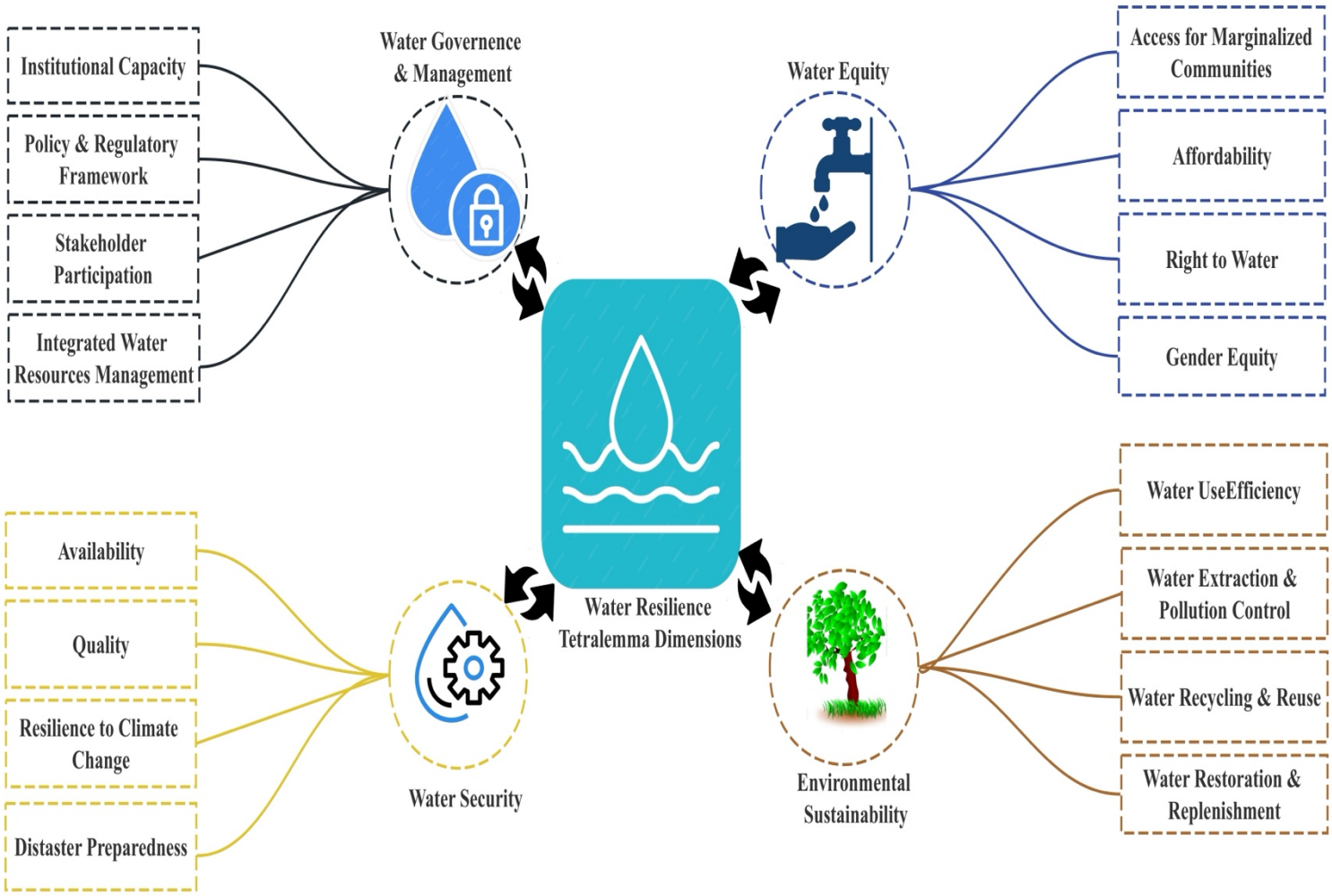


Figure 4: Water tetralemma criteria and sub-criteria.

2.2.1 Sub-Criteria for Water Security

Water security is a society's ability to maintain sustainable access to sufficient water of acceptable quality for drinking, livelihoods, ecosystems, and production, while mitigating pollution, droughts, and flood risks (Babuna et al., 2023). A water-secure system ensures present and future access to high-quality water while managing associated costs. Four sub-criteria operationalize this dimension: availability, water quality, resilience to climate change, and disaster preparedness, covering resource endowment and risk management. These sub-criteria are informed by and consistent with United Nations Water and the Moroccan National Water Strategy, which

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emphasize adequate water quantity and quality and preparedness for climate and disaster risks (UN Water, 2013).

Water availability refers to ensuring a sufficient and reliable supply of water to meet the present and future needs across all sectors. This criterion addresses the ability of supply systems and natural hydrological resources to deliver water without substantial deficits. Water quality concerns maintaining or improving water for its intended uses, including drinking, irrigation, industrial applications, and ecosystem health. This sub-criterion assesses the extent to which technology sustains or enhances chemical, physical, and biological water quality parameters. Resilience to climate change is the capacity to withstand or adapt to altered rainfall, more frequent droughts, or severe weather events (UN, 2016). This criterion evaluates technology performance under climatic variability and long-term change. Disaster preparedness is the extent to which the technology or system is equipped to respond to and swiftly recover from floods, storms, droughts, and contamination events. It encompasses emergency response measures, infrastructure robustness, and redundancy to maintain services during crises. Preparedness protects water supply and quality from significant disruption by sudden shocks, contributing to water security.

2.2.2 Sub-Criteria for Water Equity

Water equity emphasizes equitable and inclusive allocation of water resources and services so that all societal groups can access safe water at a reasonable cost. It recognizes water access as a fundamental human right essential to well-being. Policies should eliminate service disparities and ensure adequate water for marginalized or vulnerable communities regardless of socioeconomic or geographic disadvantage (Manero & Wheeler, 2022). Four sub-criteria are used: access for marginalized communities, affordability, gender equity, and the right to water. Access for marginalized communities is the degree to which water services and benefits reach underrepresented

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or vulnerable groups, including rural populations, low-income households, informal settlements, indigenous communities, and other marginalized populations. This criterion assesses the capacity of sustainable water technologies to improve supply or treatment for populations currently lacking sufficient service. Affordability concerns infrastructure, operations, and end-user tariff costs that remain manageable across demographic groups, especially economically disadvantaged households. It examines whether technology implementation maintains affordable water prices for low-income households and keeps essential water uses accessible to all. Gender equity assesses the degree to which the water solution facilitates gender equality in access to and management of water resources. Globally, women and girls frequently shoulder unequal water collection and face greater hardships during water insecurity or contamination. The right to water aligns with the human right to safe water, ensuring that everyone can access a minimum standard of safe, acceptable, physically accessible, and affordable water for personal and domestic use. This comprehensive sub-criterion encompasses access, affordability, and non-discrimination.

2.2.3 Sub-Criteria for Environmental Sustainability

Environmental sustainability involves managing and using water to conserve ecosystems, sustain the resource base over the long term, and reduce adverse environmental effects (M. Karimi et al., 2024). It aims to meet current water requirements while maintaining aquatic and terrestrial ecosystem integrity and the capacity of future generations to fulfill their needs.

A sustainable water system aligns human consumption with nature's regenerative capacity, preventing over-extraction and pollution of rivers, lakes, aquifers, and oceans (Wang et al., 2025; Farid et al., 2024). Four sub-criteria assess this dimension: water extraction and pollution control, water use efficiency, water restoration and replenishment, and water recycling and reuse.

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Water extraction and pollution control assess the extent to which sustainable water technologies reduce unsustainable abstraction from the environment and mitigate water body pollution. Two interconnected aspects are considered: (1) restricting extraction from natural sources, including rivers and aquifers, to prevent ecological stress, overdraft, and habitat loss; and (2) minimizing pollutant discharges into the environment. Water use efficiency assesses whether a technology or practice achieves equivalent outcomes or services with less water consumption or produces greater results with the same amount of water. Water recycling and reuse assess the potential of alternatives to recycle water and encourage reuse, supporting a circular water economy. Recycling involves treating wastewater or greywater to a standard appropriate for reuse in applications including industrial process water, agricultural irrigation, groundwater recharge, and potentially potable reuse (Najafabadi et al., 2023).

Environmental sustainability assessment considers how effectively technologies protect and regenerate the water environment. Technologies receive positive evaluations for minimizing abstraction and pollution, improving efficiency, restoring natural water systems, and promoting reuse.

2.2.4 Sub-Criteria for Water Governance and Management

Water governance and management encompass the institutions, policies, and processes that guide water resource decisions and implementation. Effective governance supports technology scalability by creating an enabling environment, securing stakeholder support, and enhancing adaptive capacity (Koebele et al., 2024). Formally, it comprises the political, social, economic, and administrative systems through which water resources are developed and managed and water services are delivered.

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Effective governance supports water security and equity through equitable allocation, accountability, and sustainable management practices (V. Karimi et al., 2024). Four sub-criteria address the governance and management dimension: policy and regulatory frameworks, institutional capacity, stakeholder participation, and integrated water resources management. Policy and regulatory frameworks assess the presence and strength of policies, laws, and regulations affecting water technology implementation. These include water laws, quality standards, allocation rules, pricing policies, and environmental guidelines. Institutional capacity concerns the ability of government agencies, water utilities, local water user associations, and other institutions to effectively manage, operate, and maintain water technologies or programs. Stakeholder participation assesses the extent of public and stakeholder engagement in decision-making, implementation, and oversight. Inclusive governance involves water users, communities, businesses, and civil society, improving transparency and acceptance of outcomes. Integrated water resources management (IWRM) entails holistic, coordinated management across sectors and scales. It recognizes connections among water supply, wastewater, agriculture, industry, land use, and the environment to support integrated planning and operation.

3. Research Methodology

This study combines fuzzy DEMATEL, fuzzy ANP, and fuzzy TOPSIS in a three-stage process to evaluate water resilience technologies. Fuzzy DEMATEL identifies causal influences among the tetralemma dimensions and their sub-criteria. These interdependencies inform fuzzy ANP, which calculates relative criterion weights while accounting for the feedback loops and interrelations revealed by DEMATEL. Fuzzy TOPSIS then uses these weights to rank the seven technologies from most to least preferred. Fuzzy set theory captures uncertainty and vagueness in expert judgments by mapping linguistic terms, such as “high influence” and “low importance,” to

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fuzzy numerical values. This integration accommodates imprecise inputs and complex criterion relationships (Alyamani et al., 2025b; Ikram & Es-sadki, 2026; Solangi & Magazzino, 2025). The following steps explain how expert inputs produce the final rankings.

3.1 Fuzzy DEMATEL

DEMATEL, developed by the Geneva Research Centre at the Battelle Memorial Institute, analyzes causal relationships among multiple factors in complex systems. It represents these relationships numerically within a structural model, often using directed graphs (digraphs) to visualize influences among criteria. To account for ambiguity in human judgment, this study integrates fuzzy set theory with DEMATEL. This fuzzy DEMATEL approach has been widely adopted in recent studies (Feng & Ma, 2020; Farooque et al., 2020; Khatun et al., 2023; Wang et al., 2024).

3.2 Fuzzy ANP

ANP extends the Analytical Hierarchy Process (AHP) to model interrelated criteria. It incorporates feedback, interactions, and interdependencies within the decision-making system and uses pairwise comparison of criteria and sub-criteria, including those that interact independently (Khanmohammadi et al., 2024).

Where interdependencies between higher- and lower-level elements make a hierarchy impractical, ANP models the decision problem as a network. Its feedback structure includes loops connecting components to themselves and cycles connecting components (Samanlioglu & Ayağ, 2021). ANP uses three matrices: the supermatrix, weighted supermatrix, and limit supermatrix. Pairwise comparisons establish the relative significance of each component in the supermatrix. Integrating fuzzy set theory allows these comparisons to use triangular fuzzy numbers (TFNs). Normalizing each column to sum to one produces the weighted supermatrix (Govindan et al., 2022).

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3.3 Fuzzy TOPSIS

TOPSIS, first proposed by Hwang & Yoon (1981) and later formulated by Chen & Hwang (1992), selects among a finite set of alternatives. The preferred alternative is closest to the ideal solution and furthest from the negative-ideal solution. To accommodate imprecision, subjectivity, and vagueness in human judgment, evaluations are typically expressed as linguistic terms that are then converted to fuzzy numbers.

Implementing fuzzy TOPSIS requires establishing the relative significance of each criterion by assigning a weight w_j to each criterion, which is typically obtained using methods such as fuzzy DEMATEL and fuzzy ANP. The fuzzy TOPSIS methodology has been effectively applied in various domains, including eco-driving solutions for reducing GHG emissions (Alyamani et al., 2025a), risk assessment of nuclear decommissioning (Awodi et al., 2023), food supplier selection (Hajiaghaei-Keshteli et al., 2023), and site selection for mobile tower installation (Dharmalingam et al., 2025).

3.4 Integrated methodology computational Phases

Phase 1: Determinants of the assessment model

After establishing the decision objective, a committee of experts selects alternatives and identifies significant evaluation criteria. Criteria are detailed in Section 2.2.

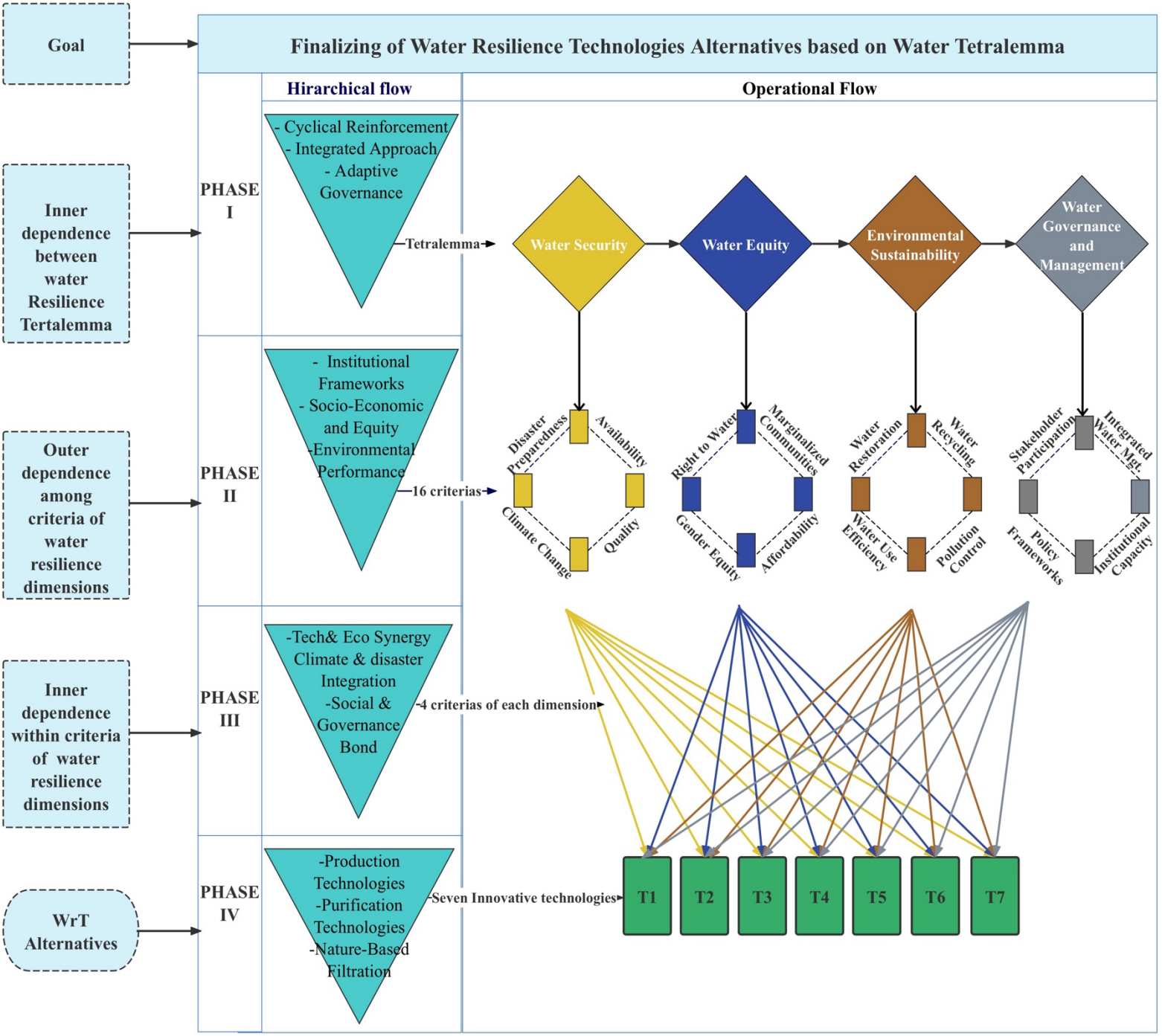
Phase 2: Creation of the Fuzzy Linguistic Scale for Evaluations

Expert judgment establishes relationships among and within the attributes through paired comparison. Table 1 presents the fuzzy linguistic scale used in this study (Chen & Hwang, 1992; Wang & Chen, 2008) and the scale quantifying these relationships. Eleven linguistic terms denote levels of influence, with corresponding fuzzy membership functions. Figure 5 organizes the four tetralemma dimensions: water security, water equity, environmental sustainability, and water

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341 governance & management, and their evaluation criteria into a hierarchy linking the goal of water
342 resilience to technology alternatives. It also distinguishes operational flows: fuzzy DEMATEL rep-
343 resents cause-effect relationships among dimensions and criteria, while fuzzy ANP represents
344 outer dependencies, feedback loops, and influences across criteria clusters. At the framework's
345 base, fuzzy TOPSIS uses ANP-derived weights to rank the seven technology alternatives across
346 all tetralemma dimensions.
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348 **Figure 5:** Sustainable water resilience technologies operational model.

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350 **Table 1:** Fuzzy-based linguistic scale.

Linguistic term	Fuzzy scales	Fuzzy Score	Interpretation
None	(0, 0, 1)	0	No importance or no effect
Very Low	(0, 0.1, 0.2)	1	Almost negligible importance/effect

Low	(0.1, 0.2, 0.3)	2	Very weak importance/effect
Fairly Low	(0.2, 0.3, 0.4)	3	Low importance/effect
More or less Low	(0.3, 0.4, 0.5)	4	Slightly below medium
Medium	(0.4, 0.5, 0.6)	5	Moderate or equal importance/effect
More or less Good	(0.5, 0.6, 0.7)	6	Somewhat high importance/effect
Fairly Good	(0.6, 0.7, 0.8)	7	Strong importance/effect
Good	(0.7, 0.8, 0.9)	8	Very strong importance/effect
Very Good	(0.8, 0.9, 1)	9	Almost the highest importance/effect
Excellent	(0.9, 1, 1)	10	Absolutely critical importance/effect

Phase 3: Establishing causal relationships through Fuzzy DEMATEL

Phase 3.1: Acquisition of the Fuzzy Direct Relation Matrix

Experts conduct pairwise comparisons to evaluate the influence and directional effects among the required criteria, resulting in an $n*n$ matrix A. Each element, denoted as, $\tilde{a}_{ij} = \left(l_{ij}, m_{ij}, u_{ij}\right)$, quantifies the extent of influence of criterion i on criterion j.

Phase 3.2: Normalization of the Fuzzy Direct Relation Matrix

After constructing the direct-relation matrix A, the next step is to normalize it according to the DEMATEL methodology.

The normalized matrix, $\tilde{X}$, is obtained from A via Equation (1). Let $\tilde{a}_{ij} = \left(l_{ij}, m_{ij}, u_{ij}\right)$ and $s = 1/\max_{1 \leqslant i \leqslant n} \sum_{j=1}^{n} u_{ij}$, then:

$$\tilde{X} = s \times \tilde{A} \tag{1}$$

Phase 3.3: Acquisition of the fuzzy total-relation matrix

After obtaining the normalized direct-relation matrix $\tilde{X}$, the fuzzy total-relation matrix $\tilde{T}$ is computed using the specified formulas, with I representing the identity matrix. The extraction process entails the definition of three distinct matrices, let $\tilde{x}_{ij} = \left(l_{ij}, m_{ij}, u_{ij}\right)$ derived from the elements of $\tilde{X}$ as outlined.

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$$X_1 = \begin{bmatrix} 0 & l_{12} & \dots & l_{1n} \\ l_{21} & 0 & \dots & l_{2n} \\ . & & & . \\ . & & & . \\ . & & & . \\ l_{n1} & l_{n2} & \dots & 0 \end{bmatrix}, X_2 = \begin{bmatrix} 0 & m_{12} & \dots & m_{1n} \\ m_{21} & 0 & \dots & m_{2n} \\ . & & & . \\ . & & & . \\ . & & & . \\ m_{n1} & m_{n2} & \dots & 0 \end{bmatrix}, \quad (2)$$

$$X_3 = \begin{bmatrix} 0 & u_{12} & \dots & u_{1n} \\ u_{21} & 0 & \dots & u_{2n} \\ . & & & . \\ . & & & . \\ . & & & . \\ u_{n1} & u_{n2} & \dots & 0 \end{bmatrix}.$$

Equation (3) defines the total-relation fuzzy matrix $\tilde{T}$ in the crisp case:

$$\tilde{T} = \tilde{X}(I - \tilde{X})^{-1} \quad (3)$$

$$\tilde{T} = \begin{bmatrix} \tilde{t}_{11} & \tilde{t}_{12} & \dots & \tilde{t}_{1n} \\ \tilde{t}_{21} & \tilde{t}_{22} & \dots & \tilde{t}_{2n} \\ . & & & . \\ . & & & . \\ . & & & . \\ \tilde{t}_{n1} & \tilde{t}_{n2} & \dots & \tilde{t}_{nn} \end{bmatrix} \quad (4)$$

where $\tilde{t}_{ij} = \left(l'_{ij}, m'_{ij}, u'_{ij}\right)$ then:

$$\text{Matrix}\left[l'_{ij}\right] = X_l(I - X_l)^{-1}, \quad (4)$$

$$\text{Matrix}\left[m'_{ij}\right] = X_m(I - X_m)^{-1} \quad (5)$$

$$\text{Matrix}\left[u'_{ij}\right] = X_u(I - X_u)^{-1} \quad (6)$$

Phase 3.4: Inner Dependency Matrix Construction

Using Equation (7), the total-relation matrix $\tilde{T}$ is initially defuzzified in this step. A normalization procedure is then applied so that each column's sum equals 1. The following equation is used to conduct the defuzzification:

$$\text{F}\left(\tilde{t}_{ij}\right) = 1/2 \int_0^1 \left(\inf_{x \in \Re} \tilde{t}_{ij}^{\alpha} + \sup_{x \in \Re} \tilde{t}_{ij}^{\alpha}\right) d\alpha \quad (7)$$

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The unweighted supermatrix for the ANP is then constructed using the inner dependence matrix that is obtained from this procedure.

Phase 4: Development of residual relationships employing fuzzy ANP

In the ANP framework, as with the AHP method, pairwise comparisons among elements at each hierarchical level are conducted to evaluate their relative importance with respect to the defined control criterion. The decision-maker's preferences within the hierarchy are efficiently represented by triangular fuzzy numbers, which quantify the relative strength of pairs of elements. Consequently, the fuzzy judgment matrix $\tilde{A}'$ is established through the subsequent pairwise comparisons:

$$\tilde{A}' = \begin{bmatrix} \tilde{a}'_{11} & \tilde{a}'_{12} & \dots & \tilde{a}'_{1n} \\ \tilde{a}'_{21} & \tilde{a}'_{22} & \dots & \tilde{a}'_{2n} \\ . & & & . \\ . & & & . \\ \tilde{a}'_{n1} & \tilde{a}'_{n2} & \dots & \tilde{a}'_{nn} \end{bmatrix} \quad (8)$$

where $\tilde{a}'_{ij} = \left(l'_{ij}, m'_{ij}, u'_{ij}\right)$ represents the relative significance of criterion i in relation to criterion j where $I = 1, 2,\dots,n$.

Phase 4.1: Relative importance weight calculation

In order to fill in the different submatrices inside the supermatrix, it is necessary to derive the most significant vectors for each and every pairwise comparison matrix. The judgment matrix is used to create the triangular fuzzy priority $\tilde{w}_k$ with $k = 1, 2,\dots,n$. These priorities are calculated using the least squares method.

$$w_k^s = \frac{\left(\prod_{i=1}^{n} a_{kj}^s\right)^{1/n}}{\sum_{i=1}^{n}\left(\prod_{i=1}^{n} a_{ij}^m\right)^{1/n}}, s \in \{l, m, u\} \quad (9)$$

The consistency ratio (CR) is calculated for each matrix and the overall hierarchy to ensure the validity of the method's results. The CR assesses the dependability of pairwise comparisons,

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with a CR under 0.10 considered acceptable; values exceeding this limit indicate inadequate comparisons. This study computed the inconsistency ratios for all comparison matrices using the mean values of the fuzzy numbers, acknowledging that the intrinsic flexibility of the lower and upper bounds precludes expecting absolute consistency.

Phase 4.2: Defuzzification of fuzzy matrix weight

The weights derived from the fuzzy matrices are defuzzified according to the procedure outlined in Equation (9). The priority for the production dimension, a factor of water security, is calculated relative to the overall objective using Equation (10) to obtain the corresponding fuzzy weight.

Phase 4.3: Resolution of the Supermatrix

As a first step in solving the supermatrix, this study normalizes each column by dividing each element by the sum of those elements. The final step involves determining a priority ranking for the alternatives by raising the normalized supermatrix to limiting powers, thereby identifying the overall priorities of the elements.

Phase 5: Supermatrix Construction

The ANP supermatrix represents the interdependencies among the four tetralemma dimensions, their sixteen sub-criteria, and the seven technology alternatives. The initial supermatrix, shown in Table S2 in the Supplementary Material, integrates the inner-dependence values derived from fuzzy DEMATEL with the outer-dependence priorities from the fuzzy ANP. After normalizing the columns, the weighted supermatrix is raised to successive powers until convergence, resulting in the limit priorities that serve as the criterion weights for the fuzzy TOPSIS assessment.

The criteria weights for selecting water security technology, obtained from the weighted supermatrix, are specified in the goal column for subsequent use in the fuzzy TOPSIS procedure.

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Phase 6: Evaluation of alternatives via fuzzy TOPSIS

The methodology, derived from Chen (2000), consists of the following steps.

Phase 6.1: Development of the fuzzy decision matrix

The evaluation of water scarcity alternatives is framed as a fuzzy MCDM problem, consisting of m alternatives and n criteria as follows:

$$\widetilde{D} = \begin{matrix} \\ A_1 \\ A_2 \\ A_3 \\ A_4 \end{matrix} \begin{matrix} \begin{matrix} C_1 & C_2 & \dots & C_n \end{matrix} \\ \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \dots & \tilde{x}_{1n} \\ \vdots & \ddots & & \\ \vdots & & \ddots & \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \dots & \tilde{x}_{mn} \end{bmatrix} \end{matrix} \tag{10}$$

The fuzzy decision matrix, represented by $\widetilde{D}$, involves assessing alternatives A with respect to criteria C using linguistic information.

Phase 6.2: Normalization of the decision matrix

$\tilde{R}$, the normalized fuzzy decision matrix, is computed using the following formula:

$$\tilde{R} = \left[\tilde{r}_{ij}\right]_{m^*n}, i = 1,2 \dots, m;\ j = 1,2 \dots n$$

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^+}, \frac{b_{ij}}{c_j^+}, \frac{c_{ij}}{c_j^+}\right), \tag{11}$$

$C_j^+ = \max_i C_{ij}$, the several criteria scales are standardized using a linear scale transformation. Thereby simplifying the normalization process and circumventing the complexities associated with the classical TOPSIS normalization formula (Chen, 2000). Chakraborty (2022) employed this method earlier. In this study, the normalized decision matrix remains constant, with the maximum value of C_{ij}=1.

Phase 6.3: Calculation of the weighted decision matrix

The weighted normalized fuzzy decision matrix was computed using Equation (11). Here, w_j is the weight for criterion j, which was obtained from the supermatrix.

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$\tilde{v}_{ij} = \tilde{r}_{ij} \otimes \tilde{w}_j$,

where $\tilde{v} = \left[\tilde{v}_{ij}\right]_{m^*n}, i = 1,2, \dots, m; j = 1,2, \dots, n.$

Phase 6.4: Calculation of distances from ideal solutions

The positive and negative ideal reference points for triangular fuzzy numbers, normalized within the [0,1] interval, are defined as follows:

$$A^+ = \{\tilde{v}_1^+, \tilde{v}_2^+, \dots \tilde{v}_n^+\}, \quad (12)$$

$$A^- = \{\tilde{v}_1^-, \tilde{v}_2^-, \dots \tilde{v}_n^-\} \quad (13)$$

where $\tilde{v}_j^+ = (1,1,1), \tilde{v}_j^- = (0,0,0)$

The subsequent phase involves evaluating the distances of the alternatives concerning the defined positive and negative ideal reference points.

$$d_i^+ = \sum_{j=1}^n d\left(\tilde{v}_{ij}, \tilde{v}_j^+\right), i = 1,2, \dots, m; j = 1,2 \dots n \quad (14)$$

$$d_i^- = \sum_{j=1}^n d\left(\tilde{v}_{ij}, \tilde{v}_j^-\right), i = 1,2 \dots m;\ j = 1,2, \dots, n \quad (15)$$

$$d(\tilde{A}, \tilde{B}) = \sqrt{\frac{1}{3}[(a_1 - b_1)^2 + (a_2 - b_2)^2 + (a_3 - b_3)^2]} \quad (16)$$

Phase 6.5: Evaluation of alternatives

Thereafter, performance indices are calculated to place the options in order of preference. The indices are then sorted from most to least significant.

4. Results

This study evaluated sustainable water technology alternatives based on the dimensions of the water tetralemma, following the computational procedures shown in Figure 5. A robust panel of 20 experts was convened to inform the evaluation process. These experts were deliberately selected to represent a cross-section of academia, industry, and government in the water sector.

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Specifically, the panel included university researchers with distinguished contributions to water resources management, ensuring deep technical and scientific insight; senior engineers and practitioners from the water industry, bringing practical and operational expertise; and officials from the Moroccan Ministry of Water and local municipal authorities. Selection criteria were stringent. Academic experts were included only if they had a record of significant research in water technology or management, and non-academic experts were required to have over 12 years of professional experience in water-related roles. This ensured that all participants were highly knowledgeable in subjects such as desalination, wastewater reuse, and water governance. The experts' input was gathered through a structured Delphi-style process. First, the panel helped validate the list of alternative technologies and define the evaluation criteria across the four tetralemma dimensions: water security, water equity, environmental sustainability, and governance, tailoring them to Morocco's context. Then, using questionnaires (see Table S1 in the Supplementary Material) and guided discussion, experts provided pairwise comparisons and judgments on the relative importance of criteria and the performance of each technology option. A fuzzy linguistic scale was employed for these evaluations to capture uncertainty and facilitate consensus. The experts engaged in iterative discussions to reconcile any differences and ultimately reached a consensus on the assigned scores and weights. The research team validated the experts' input by checking consistency ratios in the analytic network process and by confirming that the agreed criteria weights reflected the experts' collective intuition. This careful selection and consensus-driven methodology lent credibility to the results, ensuring that the ranking of sustainable water technologies for Morocco was grounded in expert knowledge and locally relevant priorities. Consequently, experts' assessments using the fuzzy linguistic scale outlined in Table 1 established the relationships among criteria and alternatives.

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This study used fuzzy DEMATEL to analyze the causal relationships between the dimensions of the water resilience tetralemma and the criteria within each dimension. This study constructed distinct fuzzy direct relation matrices for each causal relationship. Table 2 presents the fuzzy direct relation matrix for the water resilience tetralemma. Afterward, the matrix was normalized using Equation (12), yielding the normalized fuzzy direct relation matrix presented in Table 3. Thus, the full fuzzy relation matrix was obtained from the normalized fuzzy direct relation matrix, as shown in Table 4. The last step in fuzzy DEMATEL is to compute the inner dependence matrix by defuzzifying the entire fuzzy relation matrix.

Table 2: Fuzzy direct relation matrix.

Water Tetralemma	Water Security	Water Equity	Environmental Sustainability	Water Governance and Management
Water Security (WS)	(0, 0, 0)	(0.4, 0.5, 0.6)	(0.6, 0.7, 0.8)	(0.5, 0.6, 0.7)
Water Equity (WE)	(0.1, 0.2, 0.3)	(0, 0, 0)	(0.2, 0.3, 0.4)	(0.4, 0.5, 0.6)
Environmental Sustainability (ES)	(0, 0.1, 0.2)	(0, 0, 1)	(0, 0, 0)	(0.1, 0.2, 0.3)
Water Governance and Management (WGM)	(0.7, 0.8, 0.9)	(0.6, 0.7, 0.8)	(0.5, 0.6, 0.7)	(0, 0, 0)

Table 3: Fuzzy normalized relation matrix.

Water Tetralemma	Water Security	Water Equity	Environmental Sustainability	Water Governance and Management
Water Security	(0,0,0)	(0.14, 0.16, 0.19)	(0.11, 0.14, 0.16)	(0.16, 0.19, 0.22)
Water Equity	(0.08, 0.11, 0.14)	(0,0,0)	(0.05, 0.08, 0.11)	(0.11, 0.14, 0.16)
Environmental Sustainability	(0.22, 0.24, 0.27)	(0.19, 0.22, 0.24)	(0,0,0)	(0.14, 0.16, 0.19)
Water Governance and Management	(0.24, 0.27, 0.27)	(0.16, 0.19, 0.22)	(0.19, 0.22, 0.24)	(0,0,0)

Table 4: Fuzzy total matrix.

Water Tetralemma	Water Security	Water Equity	Environmental Sustainability	Water Governance and Management
Water Security (WS)	(0.24, 0.27, 0.30)	(0.24, 0.27, 0.30)	(0.22, 0.24, 0.27)	(0.24, 0.27, 0.30)

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Water Equity (WE)	(0.15, 0.17, 0.20)	(0.18, 0.20, 0.23)	(0.11, 0.13, 0.15)	(0.15, 0.17, 0.20)
Environmental Sustainability (ES)	(0.27, 0.30, 0.33)	(0.24, 0.27, 0.30)	(0.32, 0.35, 0.38)	(0.15, 0.17, 0.20)
Water Governance and Management (WGM)	(0.27, 0.30, 0.33)	(0.22, 0.24, 0.27)	(0.24, 0.27, 0.30)	(0.30, 0.33, 0.36)

Table 5 presents the inner dependence matrix for the dimensions of the water resilience tetralemma. This study used a comparable methodology to obtain the inner dependence matrices for the criteria within each dimension. The ANP, as explained in phase 4 of the integrated methodology, was used to determine how the different parts of the water resilience tetralemma affect one another. Expert reviews utilized a fuzzy language scale to examine external dependencies related to water security criteria, including quality, availability, adaptability to climate change, and disaster preparedness. This study subsequently implemented phase 3.1 to extract the relative weights from the resulting fuzzy matrices. Equation (12) was used to address the non-linear priority in this process and then to normalize the obtained values. The weight vector for the four main dimensions of the water resilience tetralemma was determined as follows: Water Security (0.244), Water Equity (0.250), Environmental Sustainability (0.221), and Water Governance and Management (0.290). This study employed a similar procedure to determine the weights for the criteria within the dimensions of water equity, environmental sustainability, and water governance and management. Conversely, the environmental sustainability dimension was more often on the receiving end of influences, indicating that environmental outcomes depend heavily on what is achieved in the other dimensions rather than driving changes themselves. This cause-effect structure informed the subsequent weighting of criteria in the ANP stage.

Table 5: Inner dependence matrix.

Water Tetralemma	Water Security	Water Equity	Environmental Sustainability	Water Governance and Management
Water Security (WS)	0.24	0.25	0.22	0.29

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Water Equity (WE)	0.17	0.20	0.19	0.18
Environmental Sustainability (ES)	0.30	0.28	0.33	0.18
Water Governance and Management (WGM)	0.29	0.27	0.26	0.35

The supermatrix is then constructed, with the inner dependency values derived from fuzzy DEMATEL and the outer dependency values coming from fuzzy ANP. This initial supermatrix, as shown in Table S2 (Supplementary Material), is raised to the power of 2p + 1 repeatedly until convergence is reached, resulting in the limit supermatrix. The weighted supermatrix values are presented in Table S3 in the Supplementary Material.

Following the acquisition of weights for the criteria, the next phase involved assessing the alternatives using fuzzy TOPSIS, which subsequently ranked them. Experts assigned scores to each sustainable water technology alternative based on all sixteen criteria across the four dimensions of the water resilience tetralemma. The evaluations facilitated the construction of a fuzzy integrated preference matrix. Table S4 (Supplementary Material) represents the fuzzy decision matrix comparing sustainable water technologies (A) against criteria (C), and the weighted normalized fuzzy decision matrix is shown in Table S5 (Supplementary Material). Subsequently, distances from the positive and negative ideal points were calculated, taking into account that the triangular fuzzy numbers are contained within the [0,1] interval, to establish the relevant ideal reference points. We ultimately calculated performance indices to rank the alternatives for sustainable water technologies. The best options from this hybrid method are shown in Table 7. They are Anaerobic Membrane Bioreactors (T3), which received a score of 0.759; Reverse/Forward Osmosis (T4), which received a score of 0.669; and Electrodialysis/Electrodialysis Reversal (T5), which received a score of 0.660.

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5. Discussion

The tetralemma ranking links technology selection to Morocco's water security and Sustainable Development Goals (SDGs). AnMBR-based reuse supports SDG 6.3 on water quality and safe reuse; energy-efficient forward osmosis supports SDGs 7 and 13 through lower energy demand and emissions; and constructed wetlands contribute to SDGs 6 and 15 through treatment and habitat creation. These benefits must be assessed alongside local implementation constraints.

In this study, each alternative was evaluated using a framework comprising four main dimensions: water security, water equity, environmental sustainability, and water governance and management. Each dimension includes four associated sub-dimensions, resulting in a total of sixteen criteria. These sub-dimensions were identified through expert consultations and a comprehensive literature review. Specifically, water security includes availability, quality, resilience to climate change, and disaster preparedness; water equity covers access for marginalized communities, affordability, gender equity, and the right to water. Environmental sustainability encompasses water extraction and pollution control, water use efficiency, water restoration and replenishment, and water recycling and reuse. Water governance and management involve policy and regulatory frameworks, institutional capacity, stakeholder participation, and integrated water resources management.

To ensure a comprehensive evaluation, the study convened a deliberately interdisciplinary panel of twenty experts from academia, government agencies, private water institutions, and local municipalities to offer insights for the analysis. The analysis employed a unified approach that integrated fuzzy set theory with three MCDM techniques: DEMATEL, ANP, and TOPSIS. The fuzzy DEMATEL method clarified internal dependencies among dimensions and sub-dimensions, while the FANP was used to determine their respective weights. The results indicated that

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548 water governance and management received the highest weight (28.5%), highlighting the critical
549 role of strategic water management in addressing water shortages, followed by water equity
550 (25.0%), water security (24.4%), and environmental sustainability (22.1%).

551 Availability received the highest global weight (14.0%), followed by water quality (10.5%),
552 policy and regulatory frameworks (9.0%), the right to water (7.8%), access for marginalized com-
553 munities (7.3%), and climate resilience (7.0%). Stakeholder participation (3.0%), disaster prepar-
554 edness (3.5%), institutional capacity (3.6%), and gender equity (3.8%) had the lowest weights.
555 These values express relative priorities within sixteen interdependent criteria, not their absolute
556 importance. Figure 6 and Table 6 report the complete results.

557 Governance's prominence suggests that technology selection should be accompanied by
558 coherent regulation and coordination across administrative levels, and the water, agriculture,
559 energy, and territorial-development sectors (Karimi et al., 2025). Institutions responsible for
560 allocation, oversight, enforcement, and adaptation shape implementation conditions. The high
561 weight of policy and regulatory frameworks is consistent with this interpretation; the weights
562 themselves do not establish implementation success.

563 **Table 6:** Weightage of water security tetralemma sub-dimensions.

Code	Sub-Indicators	Weight	Rank
WS1	Availability	0.140	1
WS2	Quality	0.105	2
WS3	Resilience to Climate Change	0.070	6
WS4	Disaster Preparedness	0.035	14
WE1	Access for Marginalized Communities	0.073	5
WE2	Affordability	0.063	7
WE3	Gender Equity	0.038	13
WE4	Right to Water	0.078	4
ES1	Water Extraction & Pollution Control	0.039	12
ES2	Water Use Efficiency	0.060	8
ES3	Water Restoration & Replenishment	0.053	9
ES4	Water Recycling & Reuse	0.048	10
WGM1	Policy and Regulatory Frameworks	0.090	3
WGM2	Institutional Capacity	0.036	15

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WGM3	Stakeholder Participation	0.030	16
WGM4	Integrated Water Resources Management	0.045	11

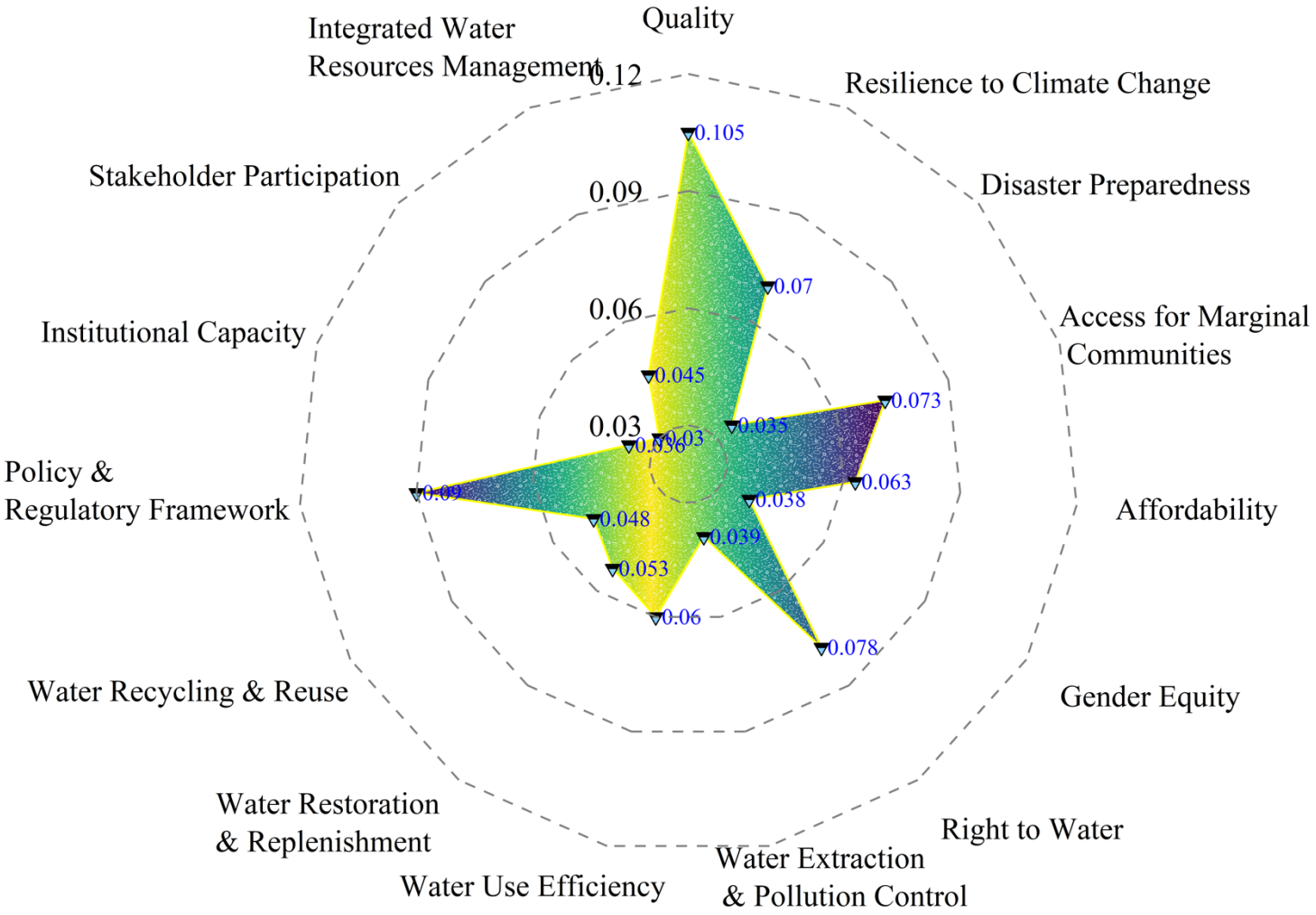


Figure 6: Weights of water tetralemma sub-dimensions.

Table 7 ranks alternatives by closeness coefficient (CCi, 0-1), with higher values indicating proximity to the ideal solution; smaller Da+ and larger Da− are preferable. AnMBRs (T3) ranked first (0.759), followed by Reverse/Forward Osmosis (T4, 0.669), Electrodialysis/Electrodialysis Reversal (T5, 0.660), Biochar and Carbon-Based Filtration (T7, 0.650), Desalination (T1, 0.564), Advanced Oxidation Processes (T2, 0.559), and Constructed Wetlands (T6, 0.542). Figure 7

illustrates this aggregate ranking. Following its review, the expert panel recommended prioritizing the leading three alternatives, particularly T3.

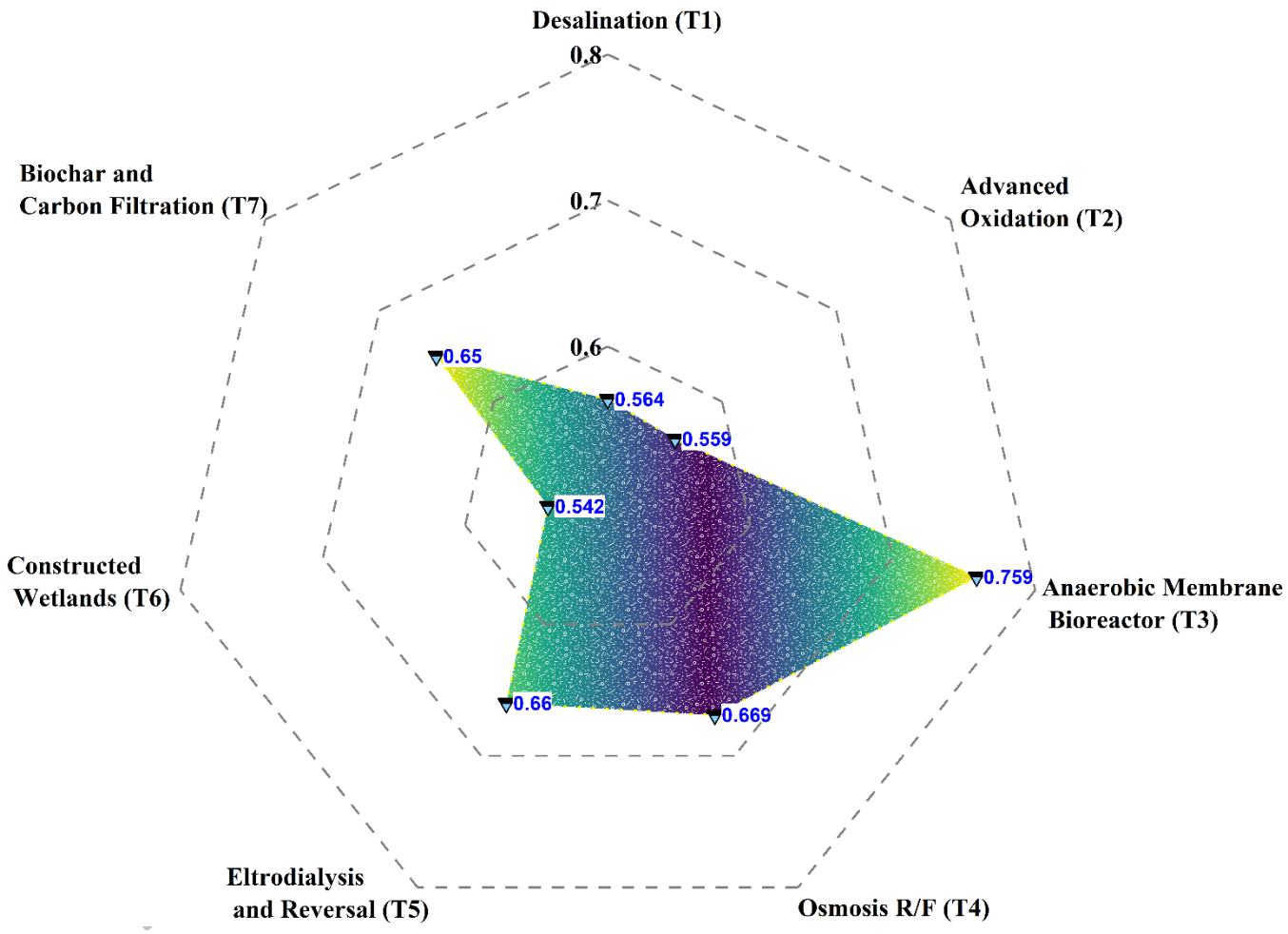
AnMBRs combine reuse, biogas recovery, and low sludge production, consistent with their potential for energy-neutral treatment (Tran et al., 2024), although fouling and maintenance remain constraints. Within T4, forward osmosis offers low-pressure treatment with potential energy and fouling advantages (Abounahia et al., 2023). Electrodialysis generally serves brackish feeds below 10,000 mg/L; when removing fewer salts, it can be cost-effective relative to high-pressure RO and achieve high recovery with relatively low energy demand, including for drinking-water supply and selective ion removal. An India solar-powered electrodialysis case reported a cost 22% below grid-powered RO (He et al., 2024). Biochar can remove heavy metals, pesticides, dyes, and other organics; some formulations outperform activated carbon for particular metals and offer carbon storage benefits (Liu & Zhang, 2022). Local production from agricultural waste may also support enterprise and reduce import dependence, helping explain its potential sustainability and equity advantages.

A leading MBBR ranking does not justify automatic deployment. Utilities, regulators, municipalities, users, and affected communities must agree on responsibilities, reuse standards, tariffs, monitoring, and risk communication (Moreira et al., 2022). Social acceptance, trust, and collective action are particularly important while allocating reclaimed water among competing uses and integrating reuse into local practices (Karimi et al., 2025).

Financing also differentiates the options. Desalination's domestic and industrial markets can support long-term revenues (Lim et al., 2025), whereas agriculture users' limited ability or willingness to pay can constrain reuse financing (Shokri & Sanavi Fard, 2023). Regulatory barriers and weaker incentives further impede reuse, making financing and equitable allocation central to

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595 comparison. AOPs including ozone, UV/H_2O_2, Fenton's reagent, and photocatalysis target persis-
596 tent organic pollutants and improve reclaimed-water safety. Their quality benefits do not inher-
597 ently increase supply; however, complexity and cost may constrain feasibility and equity (Rizzo,
598 2022). These tradeoffs help explain their lower aggregate ranking within a framework that also
599 values availability and access.
600



601

602 **Figure 7:** Tetralemma Water Resilience technologies final ranking.

603

Constructed wetlands face a distinct tradeoff in arid settings: evapotranspiration can reduce water available for reuse. Hot-climate studies report losses exceeding 40% of inflow (Mittal et al., 2023), a substantial constraint where maximizing water recovery is a priority.

The rankings therefore require interpretation against upfront costs, operation and maintenance needs, regulation, and public acceptance. Leading alternatives warrant further assessment and capacity-building support, while lower-ranked technologies may retain value for specific treatment needs and local conditions.

Pilot deployment should combine technical assessment with basin-level coordination, transparent monitoring, stakeholder consultation, and clear reclaimed-water allocation rules (Menon & Kalyanraman, 2025). These arrangements improve accountability, acceptance, and learning among agencies, operators, and users, helping translate the ranking into feasible investments.

Table 7: Final ranking of sustainable water technology alternatives.

Code	Proposed Water Technologies	Da+	Da-	CCi	Rank
T1	Desalination	0.149	0.193	0.564	5
T2	Advanced Oxidation Processes	0.138	0.175	0.559	6
T3	Anaerobic Membrane Bioreactors	0.074	0.233	0.759	1
T4	Reverse/Forward Osmosis	0.103	0.208	0.669	2
T5	Electrodialysis and Electrodialysis Reversal	0.107	0.208	0.660	3
T6	Constructed Wetlands	0.153	0.181	0.542	7
T7	Biochar and Carbon-Based Filtration	0.107	0.199	0.650	4

5.1 Sensitivity Analysis

To evaluate the robustness of the fuzzy TOPSIS rankings, five weighting scenarios were defined based on common emphases in water resilience decision-making. These included a neutral baseline with equal weights for all four tetralemma dimensions as well as four biased scenarios, each of which focused on one dimension: (a) Water Governance and Management, which focused

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on strategic planning; (b) Water Equity, which focused on social justice; (c) Environmental Sustainability, which focused on eco-centricity; and (d) Water Security & Climate Resilience, which focused on crisis response. Fuzzy TOPSIS distances and closeness coefficients were recalculated for each scenario. AnMBRs (T3) remained first in all five scenarios (Table 8).

The remaining rankings varied with the weighting scheme. Biochar filtration (T7) ranked second under equity priorities and third under environmental priorities, while desalination (T1) ranked second under security priorities. T4 and T5 fell to fourth in some scenarios. The results support the stability of the preferred alternative under the reported scenarios, while subsequent priorities remain sensitive to decision-makers' preferences.

Table 8: Comparison of alternative rankings under different weighting scenarios.

Technology Alternative	Equal Weights (Neutral)	Governance Priority (Strategic)	Equity Priority (Social)	Environment Priority (Eco-centric)	Security Priority (Crisis)
Desalination (T1)	5	4	6	7	2
Advanced Oxidation (T2)	6	6	7	5	7
AnMBR-Wastewater Reuse (T3)	1	1	1	1	1
Reverse/Forward Osmosis (T4)	2	3	3	2	4
Electrodialysis (T5)	3	2	4	4	3
Constructed Wetlands (T6)	7	7	5	6	5
Biochar Filtration (T7)	4	5	2	3	6

6. Conclusions and Policy Implications

The integrated fuzzy DEMATEL-ANP-TOPSIS framework evaluates water technologies across security, equity, environmental sustainability, and governance while accounting for interdependencies and uncertain expert judgments. AnMBRs ranked first, followed by Reverse/Forward Osmosis and Electrodialysis/Electrodialysis Reversal. Governance received the highest dimensional weight, supporting joint consideration of technology and institutional readiness. The

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tetralemma offers a transparent planning structure that may be adapted to other regions and infrastructure sectors; its findings support context-specific pilots and appraisal before scale-up.

Managers should therefore prioritize these technologies for pilot projects and scale-up initiatives. The analysis also revealed that governance and institutional factors are the most influential in determining the success of water technologies, as well as in ensuring social equity and water supply reliability. This highlights a key insight: addressing Morocco's water crisis requires selecting effective technologies and establishing enabling conditions such as policy support, institutional capacity, and social acceptance that allow these technologies to realize their full potential. The study's holistic framework addresses a critical gap by providing a transparent, evidence-based tool for water-sector decision-making, moving beyond ad hoc or single-criterion approaches.

The findings have significant practical implications for Morocco's water resilience strategy. Immediate priorities are to align wastewater-reuse regulations, pilot leading technologies, particularly AnMBR systems offering reuse and biogas recovery, and address severe shortages in urban and peri-urban areas. Treatment and distribution improvements should reduce avoidable losses, while contingency plans and public conservation initiatives prepare for drought and demand associated with the 2030 FIFA World Cup. A coordination mechanism spanning ministries, basin agencies, utilities, municipalities, and private operators should align licensing, communication, oversight, and operational readiness. Partnerships with academic institutions and technology providers can support these pilots.

Medium-term priorities are blended finance, targeted subsidies or tax incentives, and procurement based on lifecycle efficiency, reuse, and energy recovery. Utilities and basin agencies need operator training in membrane management, water-quality monitoring, risk communication, and lifecycle costs, together with maintenance capacity and shared data systems. Stakeholders

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should participate before siting and tariff decisions to strengthen acceptance and operational arrangements. Assessment of Reverse/Forward Osmosis and electrodialysis should consider coastal and arid inland treatment needs alongside their energy requirements.

Over the longer term, national planning should integrate the tetralemma with basin resilience strategies, renewable energy, social inclusion targets, and periodic assessment of drought risk, affordability, environmental performance, and institutional capacity. A circular water strategy can combine reuse, decentralized treatment, brackish-water desalination, and ecosystem protection. Explicit benchmarks across all four dimensions would support continuing evaluation beyond individual projects and immediate shortages.

7. Research limitations and future directions

This study presents important insights into the application of sustainable water resilience technologies in Morocco using a comprehensive tetralemma evaluation framework. Despite these contributions, certain limitations should be acknowledged. The criteria and weights reflect Morocco's context and may not transfer beyond similar arid developing regions. Applications elsewhere should reassess priorities against local socio-environmental conditions and compare results to refine the framework. The small expert panel (n=20) introduces subjectivity despite careful selection and fuzzy consensus. A larger or differently composed group could produce different rankings. Future work should include more experts and community stakeholders to examine this sensitivity.

Expert-based fuzzy DEMATEL, ANP, and TOPSIS remain susceptible to judgment bias. Comparisons with complementary approaches, such as fuzzy PROMETHEE or Bayesian networks, could test the findings and clarify factors affecting technology adoption.

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Future work could combine AI, remote sensing, and on-site sensors to update assessments as conditions change. Soil moisture, vegetation stress, reservoir storage, and groundwater anomalies could complement utility measurements of flow, pressure, leakage, effluent quality, and energy use. Digital twins or system dynamics models could examine tariffs, investment schedules, reuse standards, drought restrictions, and inter-agency coordination before implementation. Such evidence would complement stakeholder judgment and support periodic recalibration of technology rankings.

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