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Enhancing Water Security and Aquifer Recharge through Rainwater Harvesting and Soil Percolation: A Sustainable Strategy for Security in Rote Ndao Regency, East Nusa Tenggara

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ABSTRACT

Water scarcity is a critical global issue, particularly in semi-arid regions, where water availability is inadequate to meet the growing demand for agricultural, domestic, and industrial uses. However, while the potential of rainwater harvesting (RWH) and soil percolation techniques to improve water supply and groundwater recharge has been explored separately, their integrated impact remains underexplored, especially in Rote Ndao Regency. This study evaluates the combined potential of RWH and soil percolation in Rote Ndao through field data collected from 100 households between March - June 2025, using RWH efficiency analysis and Darcy's Law for soil percolation simulations. The results indicate that metal roofs provide the highest efficiency for RWH, yielding 52,800 liters per household annually, and approximately 12.9 million liters of harvested rainwater can percolate into shallow aquifers annually. Furthermore, the sustainability of these integrated systems was evaluated across five key dimensions using Multidimensional Scaling (MDS) and RAPFISH methods, revealing the following sustainability indices: political (49.97), ecological (44.29), economic (63.02), socio-cultural (55.72), and technology (49.6). These results highlight that political and ecological dimension face significant challenges, with political sustainability remaining the most critical hurdle. This study contributes valuable insights into integrating RWH and soil percolation to enhance water security, agricultural productivity, and community resilience, with practical implications for water management strategies and policy in semi-arid regions.

1. INTRODUCTION

Water scarcity is a growing global crisis, with a significant impact on over two billion people worldwide. The accelerating pressures of climate change, population growth, and environmental degradation are exacerbating the issue, as the availability of freshwater resources becomes increasingly limited. According to the United Nations, approximately 40% of the global population already faces severe water stress for at least one month per year, a situation projected to worsen due to climate change. This is particularly concerning in arid and semi-arid regions, where water resources are already scarce, and the need for sustainable water management solutions is more urgent than ever [1, 2]. In these areas, the demand for water surpasses the available supply, affecting agriculture, ecosystems, and local populations' ability to meet their basic needs. As such, the development of innovative strategies for efficient water management is critical to ensuring water security in the face of growing environmental and socio-economic challenges [3-9].

Rote Ndao Regency in East Nusa Tenggara, Indonesia, is one such region grappling with significant water scarcity challenges. The semi-arid climate, irregular rainfall patterns, and limited infrastructure for water storage and distribution have made it difficult to maintain a stable water supply. With agriculture being the primary livelihood for the local population, water shortages during the dry season heavily impact food security and economic stability. While rainwater harvesting (RWH) has been proposed as a potential solution to mitigate water shortages, it remains insufficient during prolonged dry periods. Combining RWH with other complementary techniques, such as soil percolation for enhanced groundwater recharge, offers a promising solution to meet the growing water demands in the region. However, there remains a lack of comprehensive studies on how these methods can work synergistically in the unique climatic and socio-economic conditions of Rote Ndao [10, 11].

The integration of RWH and soil percolation for improving water security has gained attention in recent studies. Soil moisture conservation practices, such as the application of biochar and other organic amendments, have been found to enhance soil's ability to retain water, thereby improving agricultural productivity and water use efficiency [12-16]. Similarly, RWH has been shown to improve water availability in arid and semi-arid regions, providing a reliable water source during the rainy season. However, research indicates that the combined use of RWH with soil percolation techniques can offer even greater benefits by enhancing groundwater recharge, which is essential for long-term water sustainability [1]. For example, studies have demonstrated that percolation techniques can help replenish shallow aquifers, improving the long-term availability of water resources [17]. Despite the promising results of these integrated approaches in other regions, such as those explored in the Mediterranean and sub-Saharan Africa [18], their specific application in the context of Rote Ndao remains under-researched.

Despite the advances in RWH and soil percolation techniques, research into their combined effects on groundwater recharge and water availability in semi-arid regions like Rote Ndao is still limited. Most studies focus on the isolated benefits of these techniques, with little attention given to how they can be integrated to provide a more sustainable water management system. There is a significant gap in understanding the synergistic effects of combining these methods, particularly in regions with unique climatic and socio-economic characteristics [19]. Moreover, while technical studies have explored the hydrological benefits of these practices, their socio-economic impacts, such as improving agricultural resilience and community livelihoods, have not been adequately addressed [20]. Filling this gap is crucial for developing practical, scalable solutions for water management in regions facing severe water scarcity.

This research makes a novel contribution to the field of water management, particularly in semi-arid regions. First, it explores the combined potential of RWH and soil percolation techniques in Rote Ndao, East Nusa Tenggara, an area that has not been extensively studied in terms of integrated water management. By examining how these two techniques can be used together, the study sheds new light on water management strategies that are suitable for regions with unique climatic and socio-economic conditions. Second, the research investigates the synergies between these methods, focusing on how their integration can enhance groundwater recharge and improve water retention. These aspects are essential for ensuring long-term water availability, especially in areas where water resources are already stretched thin. Finally, the study evaluates the socio-economic benefits of these integrated approaches, particularly in terms of boosting agricultural productivity and enhancing community resilience. Understanding how these water management strategies can contribute to food security and reduce the vulnerability of local populations to water scarcity is crucial for developing effective and sustainable solutions in regions facing similar challenges [21]. This multifaceted approach to water management provides valuable insights for policymakers and communities striving for more resilient and adaptive water systems.

The primary objective of this study is to assess the combined effectiveness of RWH and soil percolation in improving water security and enhancing groundwater recharge in Rote Ndao. This research will focus on quantifying the impact of these methods on groundwater recharge, soil moisture retention, and agricultural productivity. Additionally, the study will examine the socio-economic impacts of these techniques, particularly in terms of improving livelihoods and food security. The research questions guiding this study are: (1) How does the integration of RWH, and soil percolation contribute to groundwater recharge and water availability in Rote Ndao? (2) What are the socio-economic benefits of these integrated water management systems for local communities, particularly in enhancing agricultural resilience and supporting rural livelihoods?

This study contributes to both theoretical and practical knowledge in the field of water management. Theoretically, it advances understanding of how integrating RWH and soil percolation can enhance groundwater recharge and water security in semi-arid regions. Methodologically, the research utilizes a combination of field data collection, hydrological modeling, and socio-economic analysis to assess the impact of these integrated techniques. Practically, the findings will provide valuable insights and recommendations for policymakers, local governments, and communities in Rote Ndao, helping to design and implement more sustainable and context-specific water management strategies.

2. LITERATURE REVIEW

RWH refers to the practice of collecting and storing rainwater for various domestic and agricultural uses, which is particularly critical in regions prone to water scarcity. In the context of semi-arid and arid areas, RWH represents an essential mechanism for mitigating water shortages by utilizing rainfall as an alternative source for household and agricultural needs. The operational definition of RWH in this study is based on collecting rainwater from building rooftops through a series of gutters and directing it into storage systems such as tanks or infiltration pits [22]. This method is recognized for its potential to address the challenges posed by water scarcity in dry regions, providing an accessible and sustainable solution to enhance water security [1].

Soil percolation, or the movement of water through the soil profile into deeper layers, plays a crucial role in recharging groundwater and improving soil moisture content. In this study, soil percolation is defined operationally as the process by which rainwater infiltrates into the soil, enhancing groundwater reserves and supporting agricultural production. Research has shown that the percolation capacity of soils depends on factors such as soil texture and structure, which directly affect the rate of water absorption and the overall efficiency of water management strategies [23]. Both RWH and soil percolation are integrative practices aimed at improving water availability, enhancing agricultural productivity, and supporting sustainable water management in semi-arid regions [24-26].

Recent studies have focused on the intersection of RWH and soil percolation as dual strategies for enhancing water sustainability. Three primary streams of research have emerged within this context. First, studies have emphasized the role of RWH as a sustainable method for mitigating water shortages, particularly in semi-arid and arid regions. Alemayehu et al. [22] highlight the potential of RWH systems to reduce dependency on conventional water sources and improve water security, especially in dryland areas.

The second stream focuses on the role of soil percolation in recharging groundwater supplies. Azim [11] explored how soil properties influence the percolation of rainwater and its subsequent contribution to groundwater replenishment. Their findings suggest that by optimizing soil management practices and enhancing percolation rates, regions suffering from low water availability can increase their groundwater storage and reduce their vulnerability to drought conditions. Furthermore, these studies demonstrate the synergy between RWH and soil percolation, underscoring the benefits of integrating these two approaches for long-term water sustainability.

Thirdly, there has been growing attention to the technical and policy challenges associated with implementing RWH and percolation systems. Studies [27-29] emphasize the need for effective governance and policy frameworks to ensure the successful implementation of RWH and percolation techniques. These studies argue that, while the potential for these technologies is vast, their integration into broader water management strategies requires coordinated efforts between local communities, government agencies, and technical experts. The challenges lie not only in technological adoption but also in overcoming political, economic, and social barriers to implementation.

This study proposes a conceptual framework that examines the interaction between RWH and soil percolation as complementary mechanisms for enhancing water sustainability in semi-arid regions. The framework posits that RWH systems capture and store rainwater for domestic use, while soil percolation facilitates the recharge of groundwater, improving both immediate water availability and long-term groundwater reserves. The efficiency of RWH systems, influenced by factors such as roofing materials and storage capacities, directly impacts the volume of water available for use. On the other hand, the effectiveness of soil percolation, determined by soil permeability and structure, influences the volume of water that can infiltrate and replenish groundwater reserves These two systems are hypothesized to function synergistically, enhancing both surface water availability and groundwater recharge, which is essential for sustaining agricultural productivity and ensuring water security in dryland areas.

In the proposed framework, the relationship between RWH and soil percolation is governed by the interplay of technical, ecological, and socio-political factors. Technologically, the design and implementation of RWH systems must align with local climatic conditions and infrastructure, while soil percolation is influenced by soil management practices, such as mulching and irrigation techniques. Ecologically, the effectiveness of these systems depends on the region's hydrological characteristics, including rainfall patterns, soil composition, and land use practices [30-32]. Finally, socio-political factors, including governance structures and community involvement, play a pivotal role in the successful adoption of these water management practices.

This study seeks to explore the integrated role of RWH and soil percolation in improving water security in semi-arid regions. It posits that the combined use of these technologies can enhance both domestic water supply and groundwater recharge, ultimately contributing to food and water security. The research will focus on understanding how RWH efficiency and soil percolation capacity interact, while also evaluating the socio-political and ecological factors that influence their successful implementation. It is expected that the findings will provide valuable insights into the operationalization of these systems, as well as inform policy recommendations for improving water management in dryland areas.

3. RESEARCH METHODS

3.1 Study area

The study was conducted in Rote Ndao Regency, located at the southernmost point of Indonesia (10°44'–11°26' S; 121°27'–123°25' E). The region is characterized by a semi-arid tropical climate with an average annual rainfall of 1,000–1,200 mm and a mean annual temperature of 27–30 ℃. The dry season lasts from April to October, and rainfall is concentrated between November and March. Geologically, the area is dominated by limestone and sandy soils with high infiltration capacity but low water retention potential. Most villages are scattered across rolling topography, and households rely heavily on rainfed agriculture and lontar (Borassus flabellifer) tapping for livelihoods.

The study focused on four representative rural villages with varying roof types and socio-economic conditions. Field data collection took place between March and June 2025.

3.2 Research design

A mixed-methods approach was employed, integrating quantitative hydrological analysis with qualitative socio-economic assessment. Quantitative data were used to estimate the potential volume of harvestable rainwater and soil percolation capacity, while qualitative analysis explored socio-cultural, institutional, and behavioral aspects influencing water management adoption.

3.3 Data collection

Data were collected through:

Household Surveys — 100 households were purposively selected based on spatial distribution and roof types (palm-leaf, metal, clay tile). Rainfall Data — Secondary data from BMKG Rote Ndao (2024) representing 10-year averages.

Soil Sampling — Five composite soil samples collected at 0–50 cm depth for hydraulic conductivity testing. Key Informant Interviews — Village leaders, local farmers, and women's groups were interviewed to assess institutional and socio-cultural dimensions of water use.

To assess infiltration capacity and groundwater recharge potential, Darcy's Law was applied:

$$Q = K_s \times A \times \frac{dh}{dl} \quad (1)$$

where,

Q = rate of water flow (m^3/s)

K_s= saturated hydraulic conductivity (m/s)

A= cross-sectional area of flow (m^2)

dh/dl= hydraulic gradient

Laboratory permeability tests yielded K_s values ranging from 10^{-4} to 10^{-6} m/s, typical for sandy-loam and calcareous soils. Simulated infiltration volumes indicate that with a 2 m^2 recharge pit and an average rainfall event of 100 mm, 12.9 million liters of rainwater could potentially percolate into shallow aquifers annually across all sampled households.

3.4 Sustainability analysis

This study employs a quantitative sustainability assessment using the Multidimensional Scaling (MDS) approach in conjunction with the RAPFISH method. These methods were selected due to their ability to integrate multiple sustainability attributes, provide expert-based assessments, and ensure robust diagnostic tools through ordination, leverage analysis, and Monte Carlo validation. The technological dimension scores reported in this study are derived from this validated framework, as summarized in Table 1.

Table 1. Sustainability dimension and attribute

Dimension	Attribute Code	Sustainability Attribute
Political	P1	Government Policies
	P2	Environmental Regulations
	P3	Policy Support
	P4	Political Awareness
	P5	Political Stability
Ecological	ECOL1	Water Availability
	ECOL2	Soil Quality
	ECOL3	Biodiversity Conservation
Economic	ECO1	Economic Benefits
	ECO2	Economic Efficiency
	ECO3	Economic Feasibility
	ECO4	Cost of Implementation
	ECO5	Long-Term Economic Viability
Socio-Cultural	SB1	Social Acceptance
	SB2	Social Inclusion
	SB3	Community Empowerment
	SB4	Cultural Awareness
	SB5	Community Involvement
Technology	T1	Technological Innovation
	T2	Technology Availability
	T3	Technological Effectiveness
	T4	Technology Accessibility
	T5	Technology Security

The study evaluates the sustainability of RWH and soil percolation systems in Rote Ndao Regency, focusing on five key dimensions: political, ecological, economic, socio-cultural, and technology. Each dimension plays a critical role in understanding the overall sustainability of water management systems in the region.

The analysis was conducted in three main stages: MDS ordination, leverage (attribute sensitivity) analysis, and Monte Carlo validation.

The research was conducted in Rote Ndao Regency, East Nusa Tenggara, Indonesia. The region plays a significant role in implementing RWH and soil percolation systems, which are essential for supporting water supply and aquifer recharge to enhance food security.

Sustainability Dimensions and Attributes

The sustainability assessment focused on five dimensions:

1. Political Dimension: This includes political factors such as government policies, political stability, and support for water management initiatives.
2. Ecological Dimension: This focuses on the availability of water resources, soil quality, and biodiversity conservation.
3. Economic Dimension: This evaluates economic factors like the cost of implementation, economic benefits, and long-term viability.
4. Socio-Cultural Dimension: This includes factors such as community involvement, cultural awareness, and social acceptance of water management systems.
5. Technology Dimension: This focuses on technological innovation, accessibility, and effectiveness in managing water resources.

Data collection was carried out through expert-based scoring, involving 20 experts with knowledge in water management, environmental governance, and rural development. These experts evaluated the sustainability of each attribute using an ordinal scale, following the RAPFISH protocol. The mean scores were aggregated to reduce individual biases.

MDS Analysis: This analysis was performed separately for each dimension using Bray-Curtis distance measures. It produced ordination plots representing the relative sustainability position of water management systems along each dimension.

Leverage (Sensitivity) Analysis: This analysis was used to identify the most sensitive attributes that influence sustainability. The impact of removing each attribute was quantified by calculating the RMS change, which shows how much each attribute influences the sustainability index.

Monte Carlo Validation: Monte Carlo simulations were conducted to test the stability and reliability of the MDS results. Random perturbations were applied to the attribute scores, and the resulting sustainability indices were compared with the original MDS estimates.

The analyses were conducted using R statistical software, with specialized packages for MDS ordination, graphical visualization, and calculation of sustainability indices.

This methodology integrates expert opinion, statistical analysis, and sustainability metrics to evaluate the effectiveness of RWH and soil percolation systems, providing actionable insights for improving food security in Rote Ndao Regency.

4. RESULT

4.1 Estimation of harvestable rainwater

The potential harvestable rainwater (V) was calculated using the standard formula:

$$V = C \times R \times A \tag{2}$$

where,

- V= volume of rainwater harvested (liters)
- C= runoff coefficient (dimensionless)
- R= annual rainfall (mm/year)
- A= roof area (m²)

Assuming $R = 1{,}100$ mm/year (1.1 m/year), the total potential for each roof type is presented in Table 2.

Table 2. Runoff coefficients and distribution of roof types

Roof Material	Runoff Coefficient (C)	Percentage of Sample (%)	Average Roof Area (m²)
Metal (zinc/iron sheet)	0.80	37	60
Palm-leaf (lontar)	0.60	60	55
Clay tile	0.75	3	70

The runoff coefficients and distribution of roof types are presented in Table 2, which provides a comprehensive overview of the variation in roofing materials within the study area.

As indicated in Table 2, metal roofs (zinc/iron sheet) exhibit the highest runoff coefficient (0.80) and constitute 37% of the sampled structures, while palm-leaf (lontar) roofs, despite representing the majority at 60%, show a comparatively lower coefficient (0.60). Clay tile roofs, although limited in occurrence (3%), demonstrate a relatively high runoff coefficient (0.75) and the largest average roof area (70 m²). Collectively, these differences highlight the significant influence of roof material characteristics on runoff generation and their implications for hydrological assessment.

The estimated annual RWH potential per household is presented in Table 3. As shown in Table 3, clay tile roofs yield the highest annual harvest (57,750 liters/year), followed closely by metal roofs (52,800 liters/year), while palm-leaf roofs generate comparatively lower volumes (36,300 liters/year). These differences are primarily attributed to variations in runoff coefficients and average roof areas among the roof types. When weighted across the 100-sample population, the results indicate an average harvesting potential of approximately 37,400 liters per household annually, corresponding to a cumulative total of about 3.74 million liters for the sampled households.

Table 3. Estimated annual rainwater harvest (RWH) per household

Roof Type	Formula Example	Estimated Volume (Liters/Year)
Metal	$0.8 \times 1.1 \times 60 \times 1000$	52,800
Palm-leaf	$0.6 \times 1.1 \times 55 \times 1000$	36,300
Clay tile	$0.75 \times 1.1 \times 70 \times 1000$	57,750

Note: The conversion factor 1000 transforms m³ into liters

To avoid interpretative ambiguity, the contribution of harvested rainwater to domestic water supply is evaluated against a clearly defined baseline of household water demand. Based on Indonesian rural water service standards, domestic water consumption typically ranges between 80–100 liters per capita per day. Assuming an average household size of four persons, the estimated annual household water demand ranges between 116,800 and 146,000 liters per year.

The estimation of harvestable rainwater potential was based on the average annual rainfall of 1,100 mm, as reported by BMKG Rote Ndao (2024). Considering the distribution of roof types among the sampled households—60% palm-leaf roofs, 37% metal roofs, and 3% clay-tile roofs—the harvestable rainwater volume was calculated using the equation $V = C \times R \times A$, where C denotes the runoff coefficient, R represents annual rainfall, and A refers to the effective roof catchment area. The calculation indicates that metal roofs exhibit the highest runoff efficiency, producing approximately 52,800 liters per household per year, followed by clay-tile roofs (57,750 L/year) and palm-leaf roofs (36,300 L/year). When weighted according to the distribution of roof types across the 100 sampled households, the total harvestable rainwater potential is estimated at approximately 3.74 million liters annually.

It should be emphasized that this value represents only the volume of rainwater that can be directly harvested from household roof catchments. In contrast, the percolation estimate of 12.9 million liters per year, presented in the subsequent section, refers to a distinct hydrological process, namely groundwater recharge generated through distributed infiltration processes at a broader landscape scale. This estimate incorporates not only roof runoff but also surface runoff from surrounding areas, infiltration structures, and natural percolation through soil layers. Therefore, the two values represent different hydrological pathways and spatial scales within the local water balance system: the 3.74 million liters per year reflects household-scale RWH, whereas the 12.9 million liters per year represents landscape-scale groundwater recharge processes. Consequently, the apparent difference in magnitude does not indicate a computational inconsistency but rather reflects the integration of complementary components within the regional hydrological system.

From a practical perspective, the harvested rainwater remains a critical supplementary water source, particularly during the prolonged dry season typical of semi-arid environments such as Rote Ndao Regency. If households install individual or communal storage tanks with capacities ranging from 2,000 to 5,000 liters, the stored rainwater could provide an important buffer for domestic uses such as bathing, washing, and cooking, thereby reducing pressure on groundwater resources and improving household-level water security.

4.2 Sustainability of potential of rainwater harvesting and soil percolation for water

The sustainability of RWH and soil percolation systems for enhancing water supply and supporting aquifer recharge, both crucial for bolstering food security in Rote Ndao Regency, East Nusa Tenggara, was evaluated using the MDS approach in conjunction with the RAPFISH method. This assessment focused on two pivotal dimensions—political and ecological—which are fundamental to the sustainability framework for water management. The analysis comprised three key stages: MDS ordination, leverage (attribute sensitivity) analysis, and Monte Carlo validation, ensuring robustness and consistency in the results.

Political Dimension

Sustainability Status of the Political Dimension

The MDS analysis revealed a sustainability index of 49.97 for the political dimension of RWH and soil percolation initiatives in Rote Ndao. As presented in Table 4, this value places the political dimension within the "Poor (Less Sustainable)" category, indicating that institutional and governance-related factors remain a limiting aspect in supporting the long-term sustainability of these initiatives.

Table 4. Sustainability index of the political dimension

Dimension	Sustainability Index	Category
Political	49.97	Poor (Less Sustainable)

Index value indicates that the political and institutional governance structures supporting these water management initiatives are currently in a vulnerable state. While the initiatives have advanced beyond a completely unsustainable phase, substantial improvements in governance and institutional frameworks are essential. The MDS ordination places the system closer to the bad reference point, underscoring the need for critical governance reforms to enhance sustainability.

Leverage Analysis of the Political Dimension

As presented in Table 5 (Leverage Analysis of the Political Dimension), Political Awareness (P4) emerges as the most influential attribute, exhibiting a very high sensitivity value of 0.8406, thereby underscoring its critical role in shaping the sustainability of RWH and soil percolation initiatives. This is followed by Political Stability (P5) and Government Policies (P1), both of which demonstrate high sensitivity levels, indicating their substantial contribution to the system's responsiveness. In contrast, Environmental Regulations (P2) and Policy Support (P3) display moderate sensitivity, suggesting a comparatively lesser, yet still meaningful, impact. Collectively, these findings highlight that attributes related to awareness, stability, and policy frameworks serve as key leverage points within the political dimension, and thus warrant prioritized consideration in strategic planning and policy formulation.

Table 5. Leverage analysis of the political dimension

Rank	Political Attribute	RMS Change	Sensitivity
1	P4 (Political Awareness)	0.8406	Very High
2	P5 (Political Stability)	0.7024	High
3	P1 (Government Policies)	0.6758	High
4	P2 (Environmental Regulations)	0.5774	Medium
5	P3 (Policy Support)	0.5774	Medium

In Table 5, the analysis reveals that P4 (Political Awareness) and P5 (Political Stability) have the greatest influence on political sustainability, as indicated by their high RMS change. These attributes are pivotal in enhancing governance and fostering institutional capacity. Conversely, P2 (Environmental Regulations) and P3 (Policy Support), while important, exhibit moderate sensitivity, suggesting that their impact on sustainability, although significant, is secondary to the foremost political factors.

Monte Carlo Analysis of the Political Dimension

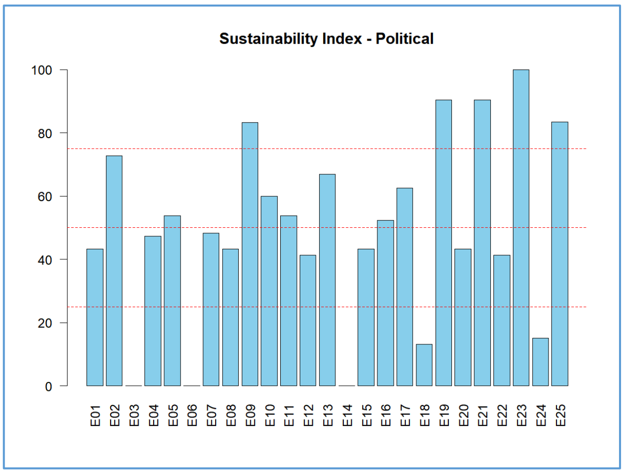
The Monte Carlo simulation results validate the stability of the political sustainability index, with minimal variation observed across different expert assessments in Table 6.

Table 6. Monte Carlo validation of the political dimension

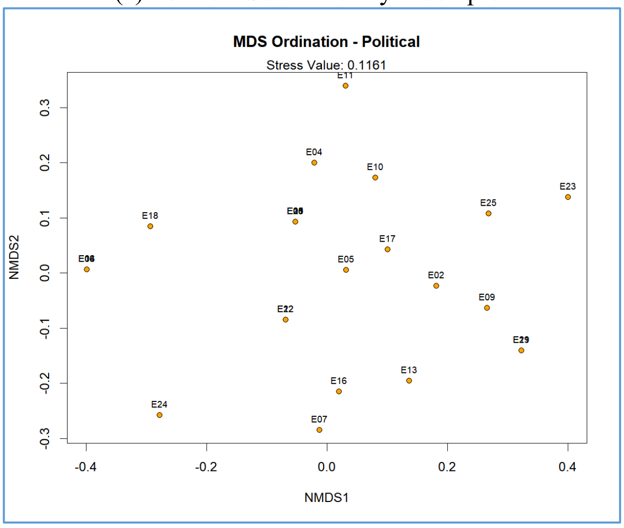
Parameter	Value
MDS Index	49.97
Monte Carlo Mean	49.8
Difference	0.1665

In Table 6, Monte Carlo mean (49.8) closely aligns with the original MDS index (49.97), confirming that expert scoring variability and potential random errors have negligible impact on the sustainability results. This consistency affirms the reliability and robustness of the political dimension assessment.

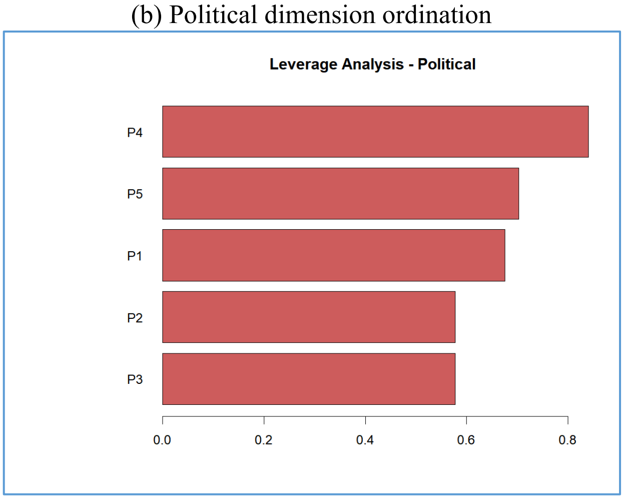
The political sustainability of RWH and soil percolation initiatives in Rote Ndao Regency was assessed through a comprehensive analysis involving MDS, leverage, and Monte Carlo validation. The Sustainability Index plot (Figure 1) reveals a moderate variation in political sustainability across locations, with some areas scoring higher than others, indicating the need for targeted governance interventions. The MDS ordination plot (Figure 2) shows that most areas are positioned closer to the bad reference point, reflecting persistent political governance challenges. Leverage analysis (Figure 3) identifies Political Awareness (P4) and Political Stability (P5) as the most influential factors in driving political sustainability, suggesting that improvements in these areas would significantly enhance overall system performance. The Monte Carlo validation (Figure 1(d)) further confirms the reliability and stability of the political sustainability index, with minimal variability across expert assessments. Together, these findings underscore the need for strengthening key political attributes to improve governance and ensure the long-term success of water management initiatives in the region.



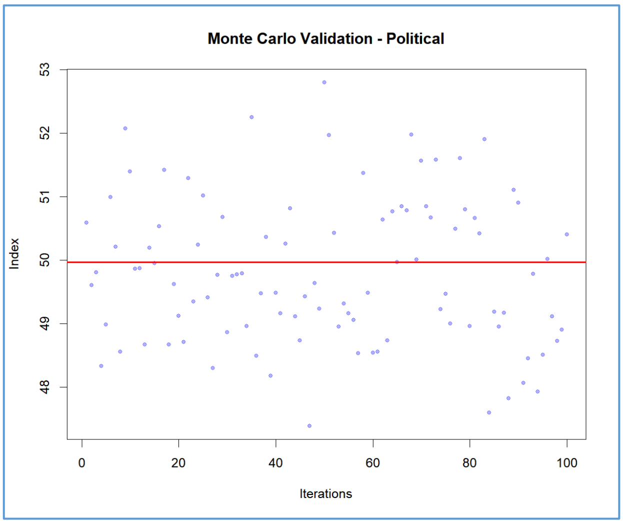
(a) Political Sustainability Index plot



(b) Political dimension ordination



(c) Leverage analysis – Political dimension



(d) Monte Carlo scatter plot

Figure 1. Political sustainability

The political sustainability of RWH and soil percolation initiatives in Rote Ndao Regency was assessed through a comprehensive analysis involving MDS, leverage, and Monte Carlo validation. The Sustainability Index plot (Figure 1(a)) reveals a moderate variation in political sustainability across locations, with some areas scoring higher than others, indicating the need for targeted governance interventions. The MDS ordination plot (Figure 1(b)) shows that most areas are positioned closer to the bad reference point, reflecting persistent political governance challenges. Leverage analysis (Figure 1(c)) identifies Political Awareness (P4) and Political Stability (P5) as the most influential factors in driving political sustainability, suggesting that improvements in these areas would significantly enhance overall system performance. The Monte Carlo validation (Figure 1(d)) further confirms the reliability and stability of the political sustainability index, with minimal variability across expert assessments. Together, these findings underscore the need for strengthening key political attributes to improve governance and ensure the long-term success of water management initiatives in the region.

Ecological Dimension

Sustainability Status of the Ecological Dimension

As shown in Table 7 (Sustainability Index of the Ecological Dimension), the ecological dimension of the RWH and soil percolation initiatives in Rote Ndao attains a sustainability index of 44.29, thereby placing it within the Poor (Less Sustainable) category. This result indicates that the ecological performance of the system remains below the desirable threshold, reflecting limited effectiveness in maintaining environmental balance and resource resilience. The relatively low index suggests the presence of critical ecological constraints, such as suboptimal water retention capacity, land degradation risks, or insufficient ecosystem support mechanisms, which may hinder long-term sustainability. Therefore, targeted ecological interventions and improved environmental management strategies are essential to enhance the sustainability status of this dimension.

In Table 7, this index indicates that the ecological aspects of these water management initiatives are currently in a vulnerable condition. While the initiatives are functioning, they have not reached a sustainable state. The MDS ordination places the system closer to the bad reference point, suggesting significant ecological challenges, such as low soil quality and limited water availability, that need to be addressed for long-term sustainability.

Table 7. Sustainability index of the ecological dimension

Dimension	Sustainability Index	Category
Ecological	44.29	Poor (Less Sustainable)

Leverage Analysis of the Ecological Dimension

Leverage analysis was conducted to identify the most impactful ecological attributes influencing the sustainability of the water management initiatives. As presented in Table 8 (Leverage (RMS change) of ecological attributes), Water Availability (ECOL1) emerges as the most influential factor, with a very high sensitivity value of 0.7348. This is followed by Soil Quality (ECOL2), which demonstrates high sensitivity, indicating its substantial contribution to ecological sustainability. Meanwhile, Biodiversity Conservation (ECOL3) shows a medium sensitivity level, suggesting a comparatively lower but still meaningful influence. Overall, these findings indicate that water availability and soil quality constitute the principal leverage points that should be prioritized to strengthen the ecological sustainability of the initiatives.

Table 8. Leverage (RMS change) of ecological attributes

Rank	Ecological Attribute	RMS Change	Sensitivity
1	ECOL1 (Water Availability)	0.7348	Very High
2	ECOL2 (Soil Quality)	0.6658	High
3	ECOL3 (Biodiversity Conservation)	0.611	Medium

The analysis reveals that Water Availability (ECOL1) and Soil Quality (ECOL2) are the most influential attributes for ecological sustainability, as indicated by their high RMS change. Improving these aspects would have the most substantial impact on the sustainability of the system. In contrast, Biodiversity Conservation (ECOL3), while still important, has a lower impact relative to the first two factors, as shown by its medium sensitivity.

Monte Carlo Analysis of the Ecological Dimension

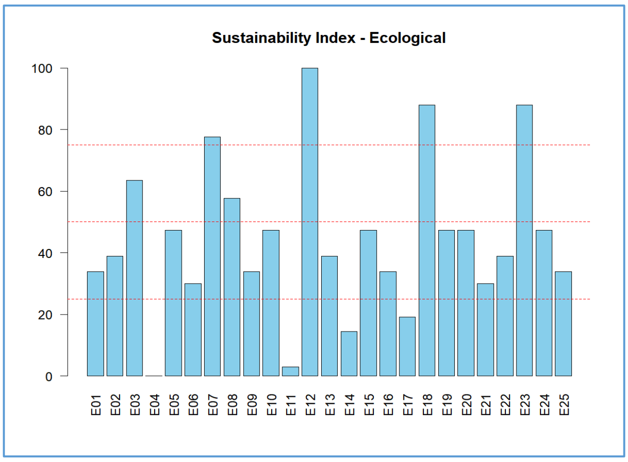
The Monte Carlo simulation results validate the stability of the ecological sustainability index, with minimal variability across different expert assessment in Table 9.

Table 9. Monte Carlo validation of the ecological dimension

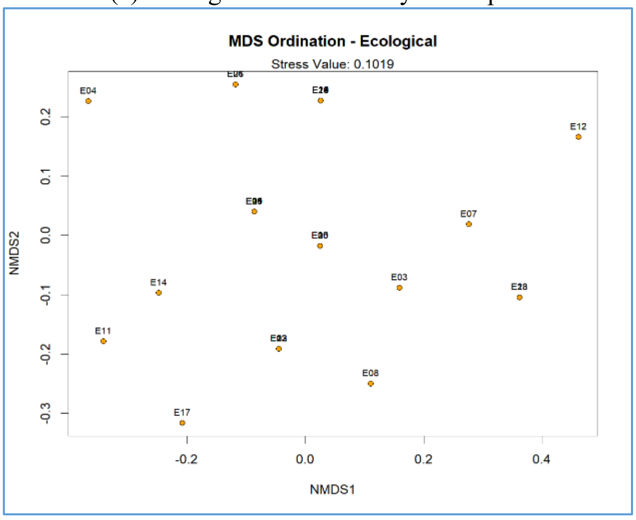
Parameter	Value
MDS Index	44.29
Monte Carlo Mean	52.38
Difference	8.0948

In Table 9, The Monte Carlo mean (52.38) is higher than the MDS index (44.29), showing a difference of 8.0948. This indicates some variability in expert assessments, though the overall result is still reliable. The confidence intervals suggest that while the ecological sustainability of the initiatives is still low, there is room for improvement with increased consistency and refined assessment techniques.

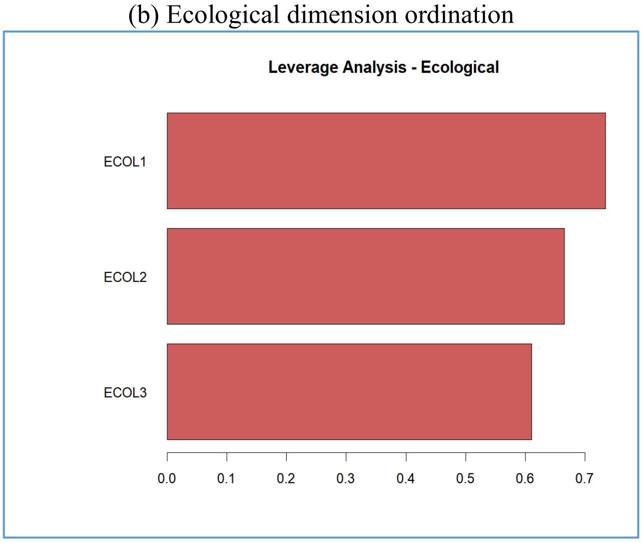
The Sustainability Index plot (Figure 2(a)) for the ecological dimension indicates a poor level of sustainability across different locations, highlighting the need for targeted ecological improvements. The MDS ordination plot (Figure 2(b)) places most locations closer to the bad reference point, reflecting persistent ecological challenges such as water scarcity and poor soil conditions. Leverage analysis (Figure 2(c)) identifies Water Availability (ECOL1) and Soil Quality (ECOL2) as the most critical factors for improving sustainability, while Biodiversity Conservation (ECOL3) plays a secondary role. Finally, the Monte Carlo validation (Figure 2(d)) confirms the stability of the ecological sustainability index, with minimal expert variability, suggesting that the findings are robust and reliable.



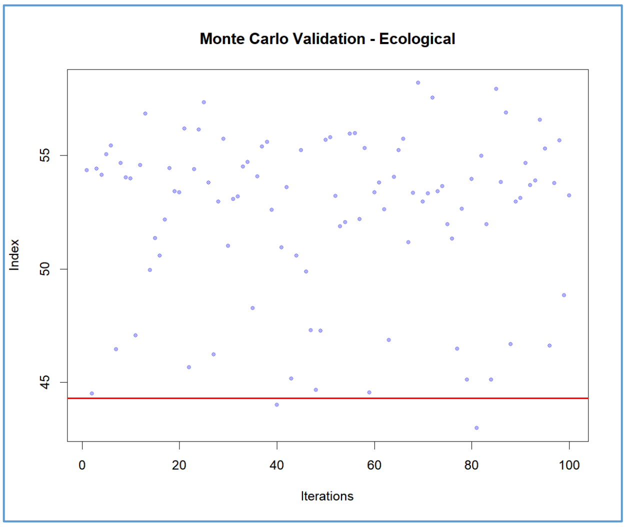
(a) Ecological Sustainability Index plot



(b) Ecological dimension ordination



(c) Leverage analysis – Ecological dimension



(d) Monte Carlo scatter plot

Figure 2. Ecological dimension sustainability

The ecological dimension of the RWH and soil percolation initiatives in Rote Ndao Regency is currently in a poor state of sustainability, with a sustainability index of 44.29. Key ecological attributes, particularly Water Availability (ECOL1) and Soil Quality (ECOL2), need to be addressed to improve sustainability. The Monte Carlo validation further supports the stability of the sustainability assessment, reinforcing the need for continued improvements in water and soil management practices to ensure long-term ecological sustainability.

Economic Dimension

Sustainability Status of the Economic Dimension

The MDS analysis revealed a sustainability index of 63.02 for the economic dimension of the RWH and soil percolation initiatives in Rote Ndao, categorizing it within the Moderately Sustainable range. As presented in Table 10 (Sustainability index of the economic dimension), this value falls within the index range of 51–75, indicating that the economic performance of the initiatives is relatively stable and capable of supporting long-term sustainability. Although the current condition reflects moderate achievement, further improvements in financial efficiency, investment capacity, and economic benefits are still required to attain a fully sustainable status.

Table 10. Sustainability index of the economic dimension

Dimension	Sustainability Index	Category
Economic	63.02	Moderately Sustainable (51-75)

The ecological sustainability condition is initially illustrated through the sustainability index plot (Figure 3(a)), which shows the distribution of index values across attributes. Furthermore, the MDS ordination results (Figure 3(b)) indicate the relative positioning of ecological attributes, reflecting their proximity to the sustainability reference point. The leverage analysis (Figure 3(c)) identifies the most influential attributes contributing to the ecological dimension, highlighting key leverage factors. Finally, the Monte Carlo validation (Figure 3(d)) confirms the stability and reliability of the model, as indicated by the limited variation in the simulation results.

Leverage analysis was performed to identify the most influential economic attributes for enhancing the sustainability of the water management initiatives. As presented in Table 11 (Leverage (RMS change) of economic attributes), the cost of implementation (ECO4) emerges as the most influential attribute, exhibiting a very high sensitivity value of 0.7483. This is followed by economic benefits (ECO1), economic feasibility (ECO3), and long-term economic viability (ECO5), which also demonstrate high to very high sensitivity levels, indicating their substantial contribution to the system. In contrast, economic efficiency (ECO2) shows a moderate sensitivity value, suggesting a comparatively lower influence. Overall, these findings highlight that cost-related and benefit-driven factors serve as key leverage points within the economic dimension and should be prioritized in sustainability planning.

Table 11. Leverage (RMS change) of economic attributes

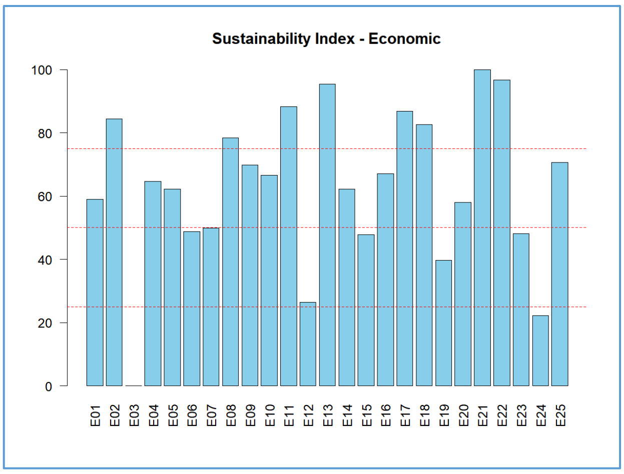
Rank	Economic Attribute	RMS Change	Sensitivity
1	ECO4 (Cost of Implementation)	0.7483	Very High
2	ECO1 (Economic Benefits)	0.7348	Very High
3	ECO3 (Economic Feasibility)	0.7348	High
4	ECO5 (Long-Term Economic Viability)	0.7348	High
5	ECO2 (Economic Efficiency)	0.6758	Medium

Monte Carlo Analysis of the Economic Dimension.

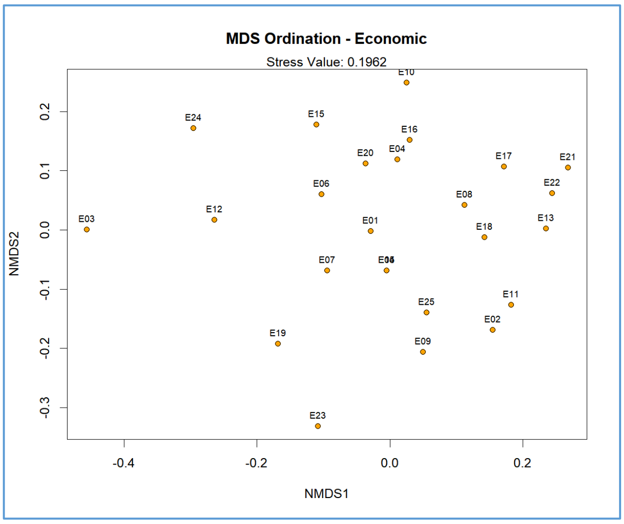
The Monte Carlo simulation results validate the stability of the economic sustainability index, with minimal variation observed across different expert assessments. As shown in Table 12 (Monte Carlo validation of the economic dimension), the MDS index value is 63.02, while the Monte Carlo mean is 59.14, resulting in a relatively small difference of 3.8819. This limited deviation indicates that the model is robust and reliable, confirming the consistency of the economic sustainability assessment despite potential uncertainties in the input data.

Table 12. Monte Carlo validation of the economic dimension

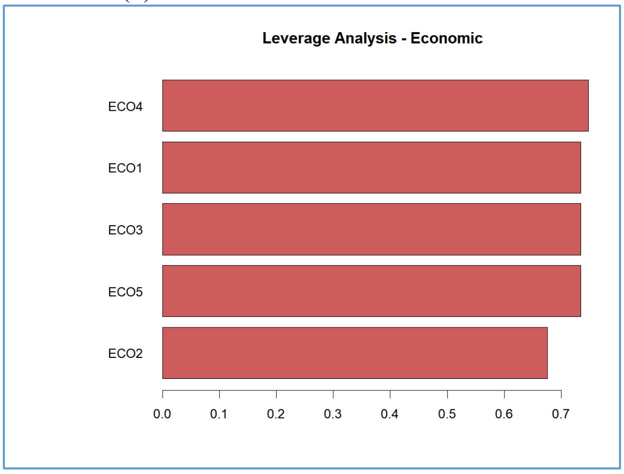
Parameter	Value
MDS Index	63.02
Monte Carlo Mean	59.14
Difference	3.8819



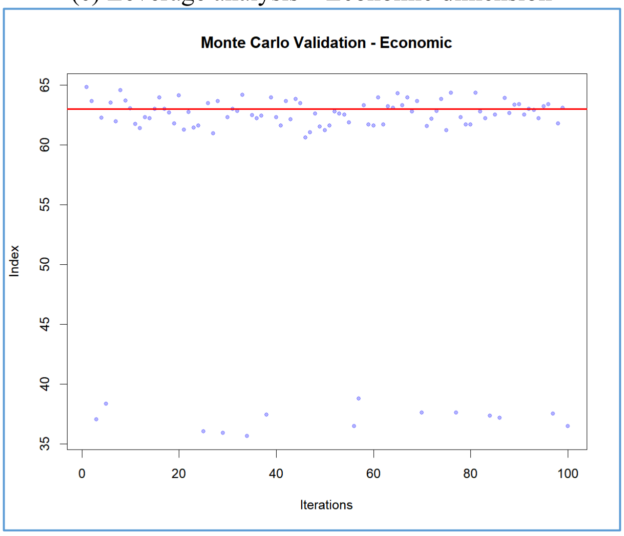
(a) Economic Sustainability Index plot



(b) Economic dimension ordination



(c) Leverage analysis – Economic dimension



(d) Monte Carlo scatter plot

Figure 3. Economic dimension sustainability

This indicates some variability in expert assessments but confirms the overall stability of the economic sustainability results. The confidence interval suggests that the assessment remains robust, although some uncertainty exists, particularly in the expert scoring of economic attributes.

The Sustainability Index plot (Figure 3(a)) for the economic dimension reveals moderate sustainability, with some regions performing better than others, highlighting the need for targeted economic interventions. The MDS ordination plot

(Figure 3(b)) positions most locations closer to the moderate reference point, indicating the presence of both strengths and challenges in the economic governance of these water management systems. Leverage analysis (Figure 3(c)) identifies Cost of Implementation (ECO4) and Economic Benefits (ECO1) as the most influential factors in improving economic sustainability, while other attributes like Economic Feasibility (ECO3) and Long-Term Viability (ECO5) have a slightly lower but still significant impact. Finally, the Monte Carlo validation (Figure 3(d)) confirms that the economic sustainability index remains stable and reliable, despite slight variability across expert assessments.

Socio-Cultural Dimension

Sustainability Status of the Socio-Cultural Dimension

The MDS analysis revealed a sustainability index of 55.72 for the socio-cultural dimension of the RWH and soil percolation initiatives in Rote Ndao, placing it within the Moderately Sustainable category. As presented in Table 13 (Sustainability index of the socio-cultural dimension), this value falls within the index range of 51–75, indicating a reasonably balanced socio-cultural condition. This suggests that community participation, local knowledge, and social acceptance are relatively well-established, although further improvements are still necessary to achieve a fully sustainable status.

Table 13. Sustainability index of the socio-cultural dimension

Dimension	Sustainability Index	Category
Socio-Cultural	55.72	Moderately Sustainable (51-75)

This index indicates that the socio-cultural aspects of these initiatives are in a moderately sustainable state. While the initiatives are not in a vulnerable condition, there is still room for improvement. The MDS ordination Figure 3(b) shows that the system is positioned relatively closer to the good reference point, suggesting that the socio-cultural governance structures are functioning fairly well but still require further strengthening to fully achieve sustainability.

Leverage Analysis of the Socio-Cultural Dimension

Leverage analysis was conducted to identify the most influential socio-cultural attributes in driving the sustainability of the water management initiatives show in Table 14.

Table 14. Leverage (RMS change) of socio-cultural attributes

Rank	Socio-Cultural Attribute	RMS Change	Sensitivity
1	SB5 (Community Involvement)	0.80	Very High
2	SB4 (Cultural Awareness)	0.7638	Very High
3	SB1 (Social Acceptance)	0.7024	High
4	SB2 (Social Inclusion)	0.688	High
5	SB3 (Community Empowerment)	0.6403	Medium

The analysis reveals that SB5 (Community Involvement) and SB4 (Cultural Awareness) are the most influential socio-cultural attributes for sustainability, with the highest RMS change values (0.80 and 0.7638, respectively). These findings suggest that enhancing community participation and cultural awareness will have the most significant impact on improving socio-cultural sustainability. Attributes like SB1 (Social Acceptance) and SB2 (Social Inclusion) are also crucial, though slightly less influential in comparison.

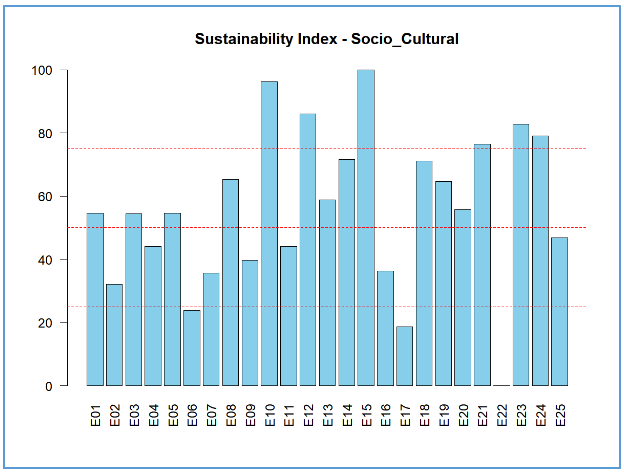
Monte Carlo Analysis of the Socio-Cultural Dimension

The Monte Carlo simulation results validate the stability of the socio-cultural sustainability index, with minimal variation observed across different expert assessments. As shown in Table 15 (Monte Carlo validation of the socio-cultural dimension), the MDS index is 55.72, while the Monte Carlo mean is 51.47, resulting in a difference of 4.2565. This relatively small deviation indicates that the model demonstrates acceptable robustness and reliability, confirming the consistency of the socio-cultural sustainability assessment despite potential uncertainties in the evaluation process.

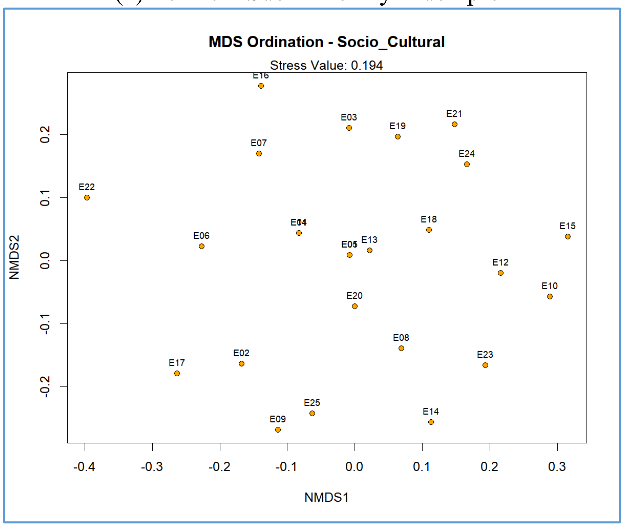
Table 15. Monte Carlo validation of the socio-cultural dimension

Parameter	Value
MDS Index	55.72
Monte Carlo Mean	51.47
Difference	4.2565

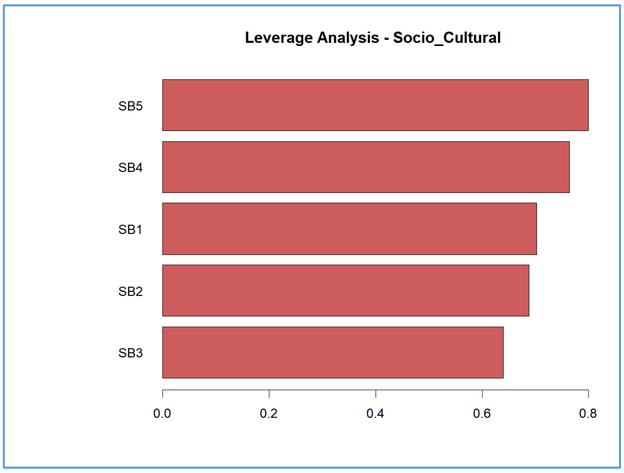
The Monte Carlo mean (51.47) is slightly lower than the MDS index (55.72), showing a difference of 4.2565. This suggests that there is some variability in expert assessments, but the overall sustainability results are still reliable.



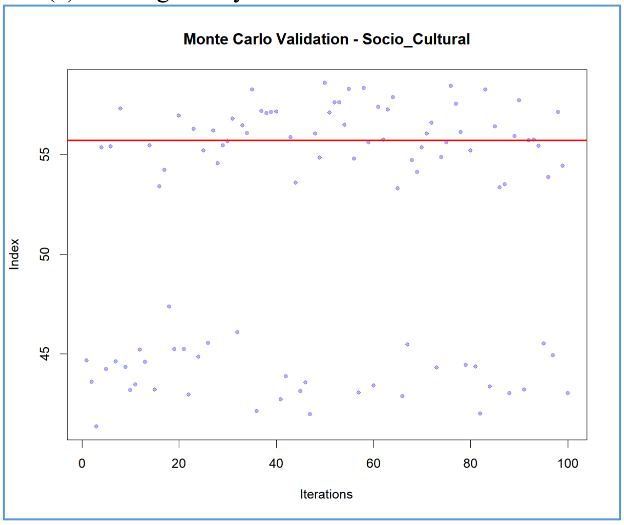
(a) Political Sustainability Index plot



(b) Political dimension ordination



(c) Leverage analysis – Socio-Cultural dimension



(d) Monte Carlo scatter plot

Figure 4. Socio-cultural sustainability

The confidence interval suggests moderate uncertainty in the assessment, indicating that while the socio-cultural dimension is relatively stable, there are areas where expert assessments vary.

The socio-cultural sustainability assessment is presented sequentially through Figure 4. The sustainability index plot (Figure 4(a)) indicates a moderate level of sustainability, with some locations performing better than others, thereby highlighting the need for targeted social and cultural interventions. Subsequently, the MDS ordination plot (Figure 4(b)) shows that most locations are positioned closer to the reference point, suggesting generally positive social dynamics while still revealing areas requiring further attention. The leverage analysis (Figure 4(c)) identifies Community Involvement (SB5) and Cultural Awareness (SB4) as the most influential factors in improving socio-cultural sustainability, whereas other attributes such as Social Acceptance (SB1) and Community Empowerment (SB3) play a secondary role. Finally, the Monte Carlo validation (Figure 4(d)) confirms the stability of the socio-cultural sustainability index, with minimal variation across expert assessments, thereby supporting the robustness and reliability of the findings.

The socio-cultural dimension of the RWH and soil percolation initiatives in Rote Ndao Regency is classified as moderately sustainable, with an index of 55.72. Key socio-cultural attributes, such as Community Involvement (SB5) and Cultural Awareness (SB4), need to be strengthened to improve sustainability. The Monte Carlo validation further supports the reliability and stability of the assessment, highlighting that gradual improvements in socio-cultural aspects will significantly improve the sustainability of these initiatives.

Technology Dimension

Sustainability Status of the Technology Dimension

The MDS analysis revealed a sustainability index of 49.6 for the technology dimension of the RWH and soil percolation initiatives in Rote Ndao, placing it within the Poor (Less Sustainable) category. As presented in Table 16 (Sustainability index of the technology dimension), this value falls within the index range of 0–50, indicating that the technological aspects of the initiatives remain below the desirable sustainability threshold. This result suggests limitations in technological innovation, accessibility, effectiveness, or supporting infrastructure, which may hinder long-term operational performance. Therefore, strategic improvements in technology adoption, system efficiency, and technical capacity are essential to enhance the sustainability status of this dimension.

Table 16. Sustainability index of the technology dimension

Dimension	Sustainability Index	Category
Technology	49.6	Poor (Less Sustainable)

This index indicates that the technological aspects of the initiatives are in a vulnerable state. The technology used in the water management system has yet to reach a sustainable level. The MDS ordination plot in Figure 5 shows that the system is positioned closer to the bad reference point, highlighting the challenges faced in the technology sector and indicating that significant improvements are required.

Leverage Analysis of the Technology Dimension

Leverage analysis was performed to identify the most influential technology attributes for enhancing sustainability. As presented in Table 17 (Leverage (RMS change) of technology attributes), Technological Innovation (T1) emerges as the most influential factor, with a very high sensitivity value of 0.8406. This is followed by Technology Accessibility (T4), which also demonstrates a very high sensitivity level of 0.7895. Furthermore, Technology Availability (T2) and Technology Security (T5) show high sensitivity values, indicating their substantial contribution to the technological dimension. In contrast, Technological Effectiveness (T3) exhibits a medium sensitivity level, suggesting a comparatively lower but still meaningful influence. Overall, these findings indicate that innovation, accessibility, and availability constitute the primary leverage points for strengthening technological sustainability.

Table 17. Leverage (RMS change) of technology attributes

Rank	Technology Attribute	RMS Change	Sensitivity
1	T1 (Technological Innovation)	0.8406	Very High
2	T4 (Technology Accessibility)	0.7895	Very High
3	T2 (Technology Availability)	0.7024	High
4	T5 (Technology Security)	0.7024	High
5	T3 (Technological Effectiveness)	0.6403	Medium

Monte Carlo Analysis of the Technology Dimension

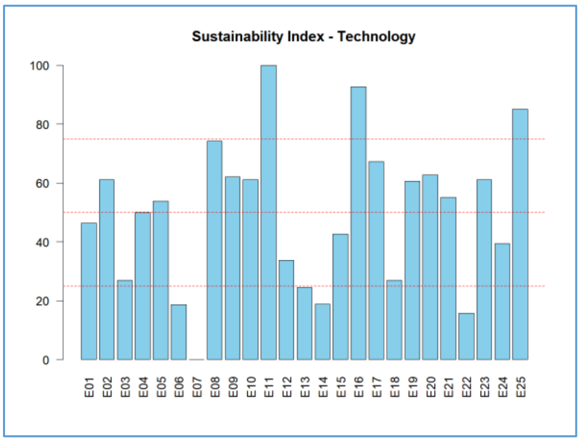
The Monte Carlo simulation results validate the stability of the technology sustainability index, with minimal variation observed across expert assessments. As shown in Table 18 (Monte Carlo validation of the technology dimension), the MDS index is 49.60, while the Monte Carlo mean is 50.57, resulting in a small difference of 0.9661. This limited deviation indicates that the model demonstrates strong robustness and reliability, confirming the consistency of the technology sustainability assessment despite potential uncertainties in the evaluation process.

Table 18. Monte Carlo validation of the technology dimension

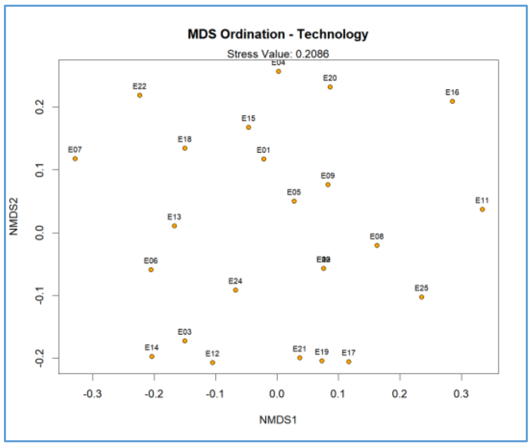
Parameter	Value
MDS Index	49.6
Monte Carlo Mean	50.57
Difference	0.9661

The Sustainability Index plot (Figure 5(a)) for the technology dimension reveals a poor sustainability status, with several locations scoring higher than others, indicating the need for focused interventions in the technological aspects of the system. The MDS ordination plot (Figure 5(b)) places most locations closer to the bad reference point, reflecting persistent challenges in technology governance. Leverage analysis (Figure 5(c)) identifies Technological Innovation (T1) and Technology Accessibility (T4) as the most influential factors for improving sustainability, suggesting that efforts to enhance these aspects will have the most significant impact. The Monte Carlo validation (Figure 5(d)) confirms that the technology sustainability index remains stable, with minimal variability across expert assessments, further affirming the reliability of the results.

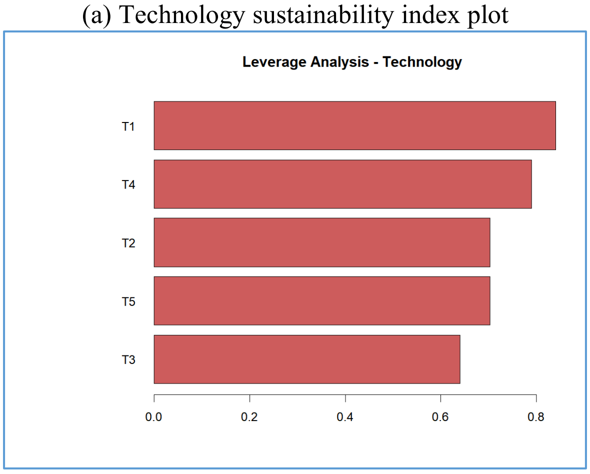
The technology dimension of the RWH and soil percolation initiatives in Rote Ndao Regency is classified as poor with an index of 49.6. Key technological attributes, such as Technological Innovation (T1) and Technology Accessibility (T4), need to be improved to enhance sustainability. The Monte Carlo validation further supports the reliability and stability of the assessment, suggesting that gradual improvements in technology innovation and accessibility will significantly improve sustainability in the long term.



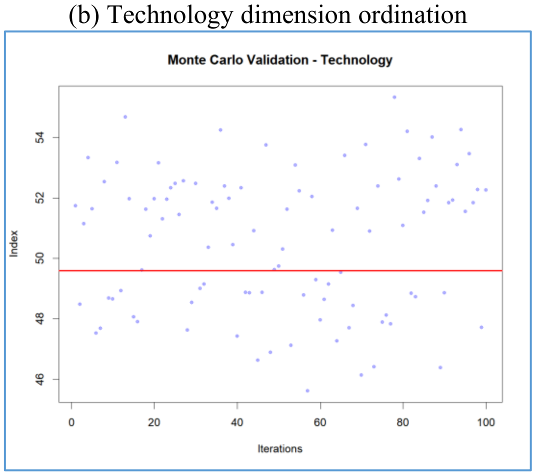
(a) Technology sustainability index plot



(b) Technology dimension ordination



(c) Leverage analysis – Technology dimension



(d) Monte Carlo scatter plot

Figure 5. Technology dimension sustainability

Table 19. Sustainability index, status, stress value, and R-square for each dimension

Dimension	Sustainability Index	Status	Stress Value	R Square
Political	49.97	Poor (Less Sustainable)	0.1161	0.9865
Ecologic9l	44.29	Poor (Less Sustainable)	0.1019	0.9896
Economic	63.02	Moderately Sustainable	0.1962	0.9615
Socio_Cultural	55.72	Moderately Sustainable	0.194	0.9624
Technology	49.6	Poor (Less Sustainable)	0.2086	0.9565

The sustainability analysis of the five dimensions reveals varying degrees of reliability and stability in the assessments, based on stress values and R-square values. As presented in Table 19, the Economic and Socio-Cultural dimensions, with stress values of 0.1962 and 0.1940, respectively, demonstrate moderate sustainability and relatively low stress levels, indicating stable results. Their R-square values of 0.9615 and 0.9624 further confirm strong model fit and robust assessments. The Political dimension stands out with the lowest stress value of 0.1161, signifying a highly stable model, supported by a very high R-square value of 0.9865, which indicates minimal expert variability and strong reliability. In contrast, the Technology dimension records a higher stress value of 0.2086, suggesting comparatively lower stability, although its R-square value of 0.9565 still reflects an acceptable model fit. Meanwhile, the Ecological dimension, despite having the lowest sustainability index (44.29), exhibits the lowest stress value of 0.1019 and the highest R-square value of 0.9896, indicating excellent model stability and minimal influence from expert variability. Overall, the consistently high R-square values across all dimensions confirm the reliability of the sustainability assessments, while the stress values suggest that further refinement may be particularly beneficial for the Technology dimension.

Figure 6 exposes a deeply problematic sustainability profile: despite a respectable Economic score of 63.02, the abysmal Ecological rating of 44.29 reveals a classic case of growth-at-all-costs myopia, where environmental degradation is systematically sacrificed for marginal economic gains. The near-failing Political (49.97) and Technology (49.60) scores—both languishing below 50—indicate institutional paralysis and technological stagnation, while the mediocre Socio_Cultural score of 55.72 suggests a hollow social fabric unable to compensate for these deficits. This radar chart does not depict sustainability; it diagnoses a system in denial, clinging to economic exceptionalism while ecological collapse looms. The irregular, lopsided shape is not a harmless statistical artifact—it is a verdict. Unless political will and technological innovation are urgently elevated to match economic ambitions, and ecological limits are treated as non-negotiable boundaries rather than optional concerns, the entire sustainability project is merely performative window-dressing.

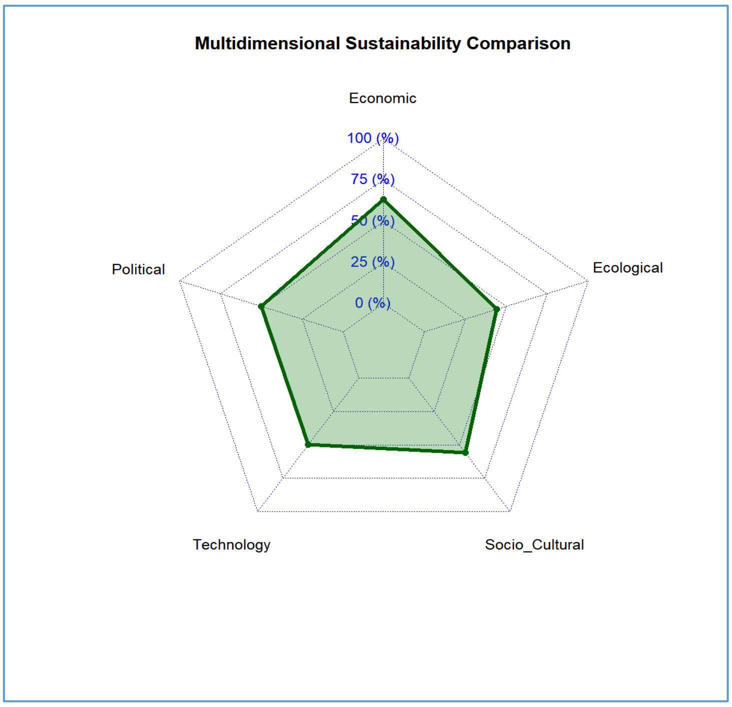


Figure 6. Multidimensional dimension sustainability

5. DISCUSSION

5.1 Hydrological role of rainwater harvesting in semi-arid water systems

The results of this study provide strong empirical evidence that RWH systems can serve as a significant decentralized water source in semi-arid environments such as Rote Ndao. Based on an annual rainfall of approximately 1,100 mm, rooftop catchment systems across the 100 sampled households generated an estimated 3.74 million liters of harvestable rainwater annually. Within the context of rural water supply systems, particularly in regions where seasonal droughts frequently disrupt groundwater availability, this volume represents a meaningful contribution to household-level water security.

From a hydrological perspective, the effectiveness of RWH systems is determined by the interaction between rainfall intensity, runoff efficiency, and effective catchment area. In this study, metal roofs exhibit the highest runoff coefficient due to their relatively smooth surfaces and low absorption capacity, allowing them to generate approximately 52,800 liters of harvestable rainwater per household annually. Clay-tile roofs produce slightly higher volumes due to their larger roof areas despite having slightly lower runoff efficiency, while palm-leaf roofs generate lower volumes because of their rougher surfaces and higher water retention properties. These results confirm that harvested water volumes are controlled not only by material characteristics but also by structural design and roof geometry.

This finding is consistent with the broader literature on decentralized water systems in dryland regions. Studies [33-37] emphasize that RWH can significantly improve water security in areas with highly variable rainfall patterns. Similarly, Studies [38-40] note that RWH systems provide a critical alternative water supply in regions where groundwater extraction has reached unsustainable levels. More recent studies further demonstrate that integrated storage systems can substantially enhance water security by capturing rainfall that would otherwise be lost as runoff [40, 41].

The significance of decentralized RWH becomes even more apparent when considered within the broader context of climate change and increasing rainfall variability. Semi-arid regions are particularly vulnerable to prolonged drought periods and erratic precipitation patterns, which can severely disrupt conventional water supply systems. In such contexts, RWH systems function not only as supplementary water sources but also as adaptive infrastructure that enhances local resilience to hydrological uncertainty [42-44].

Moreover, decentralized RWH offers an important advantage over centralized infrastructure systems. Large-scale water supply networks often require significant financial investments and complex institutional arrangements. In contrast, rooftop harvesting systems can be implemented at relatively low cost and operate directly at the household level. As emphasized by Khan et al. [45] and Revandh and Katturajan [46] decentralized water management strategies are increasingly recognized as effective solutions for improving water security in both rural and peri-urban environments. The findings of the present study reinforce this argument by demonstrating that relatively simple household-scale technologies can generate substantial water volumes in semi-arid landscapes.

5.2 Integration of rainwater harvesting and groundwater recharge mechanisms

Beyond its direct contribution to domestic water supply, RWH also plays a crucial role in supporting groundwater recharge through soil infiltration processes. The infiltration simulation conducted using the Darcy-based approach indicates that approximately 12.9 million liters of water can potentially percolate into shallow aquifers annually across the study area. This result demonstrates that the hydrological significance of RWH extends far beyond household water supply and contributes to the replenishment of local groundwater reserves.

It is important to emphasize that the 3.74 million liters of harvested rainwater and the 12.9 million liters of percolated water represent two different components of the regional water balance system. The former reflects water captured directly from rooftop catchments, whereas the latter represents groundwater recharge resulting from infiltration processes occurring across the broader landscape. These processes operate at different spatial scales but remain hydrologically interconnected. While rooftop systems capture rainfall at the household level, infiltration structures and natural soil processes facilitate the downward movement of water into deeper soil layers and ultimately into aquifers.

The integration of these two mechanisms is particularly important in semi-arid regions where groundwater often represents the primary long-term water reserve, serving as a critical buffer against seasonal and inter-annual rainfall variability. As Kant and Wrat [47] convincingly demonstrate in their review of integrated water management strategies, sustainable water management in arid environments cannot rely on surface water alone due to high evaporation losses and erratic precipitation; instead, it requires a combined strategy that links surface water capture through structures such as micro-catchments, sand dams, and runoff farming systems with deliberate groundwater recharge mechanisms designed to enhance natural infiltration. This conclusion is further strengthened by Gebreslassie et al. [48], who synthesize current practices from multiple semi-arid case studies and show that integrated approaches not only improve water availability but also reduce the environmental footprint of water extraction. Extending this logic to hydrological process modeling. Prajith et al. [49] provided quantitative evidence that infiltration-based water management systems, including percolation tanks and recharge wells, play a critical role in maintaining groundwater balance, especially under conditions of increasing climatic variability where traditional rainfall-fed systems become increasingly unreliable. Supporting this multi-disciplinary, Tsihrintzis [50] argued from an integrated water resources management framework that infiltration should be recognized as a fundamental process linking surface hydrology, soil moisture dynamics, and groundwater storage, and that any water management system failing to account for these connections is inherently unsustainable in the long term.

The effectiveness of infiltration processes in this study is strongly influenced by soil hydraulic properties. Laboratory analyses revealed hydraulic conductivity values ranging from 10^{-4} to 10^{-6} m/s, indicating significant variability in infiltration capacity across the study area. Sandy soils demonstrate relatively high permeability, allowing rapid infiltration and efficient groundwater recharge, whereas sandy loam and calcareous soils exhibit slower percolation rates. These findings suggest that local soil conditions represent a critical factor in determining the effectiveness of groundwater recharge strategies.

This observation aligns with the findings [51], which emphasize that infiltration-based water management systems must be carefully designed to match local soil characteristics in order to maximize recharge efficiency. Furthermore, studies on soil management in semi-arid environments indicate that improving soil structure and organic matter content can significantly enhance infiltration capacity and water retention [52]. Therefore, effective groundwater recharge strategies must combine hydrological infrastructure with soil management practices.

The integration of RWH with infiltration systems also has important implications for agricultural sustainability. Water availability remains one of the most significant constraints on agricultural productivity in semi-arid regions. Study [53] demonstrated that improved water management systems can substantially enhance agricultural resilience by stabilizing water availability during dry periods. In this context, the integrated system examined in this study contributes not only to household water security but also to the broader stability of regional food production systems.

5.3 Multidimensional sustainability of integrated water management systems

While the hydrological potential of RWH and soil percolation systems in Rote Ndao is substantial, the sustainability analysis reveals that the long-term success of these systems depends on multiple interacting dimensions. The RAPFISH–MDS assessment indicates varying levels of sustainability across political, ecological, economic, socio-cultural, and technological dimensions, highlighting the complex nature of water management in semi-arid regions.

The political dimension, with a sustainability index of 49.97, falls within the less sustainable category, indicating that governance structures supporting water management initiatives remain relatively weak. Leverage analysis identifies political awareness and political stability as the most influential attributes affecting sustainability outcomes. These findings confirm that effective water management systems require not only technical solutions but also strong institutional support. The study [54] similarly emphasized that governance frameworks play a central role in determining the long-term viability of water management initiatives.

The ecological dimension, with a sustainability index of 44.29, also falls within the less sustainable category, reflecting persistent environmental constraints such as declining soil quality and limited water availability. Ecological leverage analysis highlights water availability and soil quality as the most critical factors influencing sustainability. These results are consistent with the findings of studies [55, 56] that emphasized that ecological resilience represents a fundamental prerequisite for sustainable water management in arid environments.

In contrast, the economic dimension, with an index value of 63.02, indicates a moderately sustainable condition. The analysis shows that implementation costs and economic benefits are the most influential factors affecting economic sustainability. This finding suggests that RWH and soil percolation systems are economically feasible within the local context, particularly when implemented at the household or community level. Similar conclusions are drawn by the studies [57, 58], which argued that decentralized water systems provide cost-effective alternatives to large-scale water infrastructure in water-scarce regions.

The socio-cultural dimension, with a sustainability index of 55.72, indicates moderate community acceptance of RWH initiatives. The leverage analysis highlights community involvement and cultural awareness as the most influential attributes shaping social sustainability. These findings reinforce the argument that community participation plays a crucial role in the long-term adoption of decentralized water management technologies [59].

However, the technology dimension remains one of the most critical constraints, with a sustainability index of 49.6, placing it within the less sustainable category. The analysis indicates that technological innovation and accessibility represent the most influential attributes affecting technological sustainability. Yadav et al. [60] emphasized that advanced technological frameworks, such as ensemble modeling for groundwater prediction, are essential for improving the reliability and efficiency of water resource management systems. By analogy, water harvesting and infiltration-based systems similarly depend on technological innovation including affordable storage technologies and monitoring infrastructure to achieve scalability and operational effectiveness. Without improved access to these technologies, the full potential of RWH systems may remain underutilized, and the technology dimension will continue to constrain overall sustainability

Taken together, these results demonstrate that the sustainability of integrated water management systems cannot be evaluated solely from a hydrological perspective. Instead, sustainable water governance requires the simultaneous strengthening of institutional frameworks, ecological resilience, economic feasibility, technological innovation, and community participation. This multidimensional perspective aligns with recent research emphasizing the importance of integrated water resource management in addressing the complex challenges of water scarcity in semi-arid environments

6. CONCLUSION

This study set out to assess the combined effectiveness of RWH and soil percolation techniques for enhancing water security and agricultural sustainability in Rote Ndao, a semi-arid region of East Nusa Tenggara, Indonesia. The findings indicate that the integration of RWH and soil percolation not only provides immediate domestic water supply but also contributes to long-term groundwater recharge, a critical factor for sustained water availability in the region.

The theoretical contribution of this study lies in its development of a comprehensive framework that integrates surface water harvesting and groundwater replenishment through soil percolation, offering new insights into sustainable water management practices in water-scarce regions. Methodologically, this research employed a combination of field data, the Darcy approach for soil percolation modeling, and the RAPFISH method to assess sustainability across political, ecological, economic, and socio-cultural dimensions. Practically, the study provides a replicable model for policymakers and local communities to implement integrated water management solutions, with a strong emphasis on the importance of governance and community involvement for the success of such initiatives.

While the results are promising, further research is needed to test the scalability of this model in other semi-arid regions with varying soil types and climatic conditions. It is also recommended that future studies explore the socio-cultural and technological factors that may influence the adoption and long-term sustainability of these systems. Additionally, policy recommendations should focus on fostering stronger governance structures and increasing political awareness to ensure the success and sustainability of water management initiatives.

This study contributes valuable insights to the field of integrated water management, with important implications for both theory and practice.

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NOMENCLATURE

Abbreviations

BMKG	Meteorological, Climatological, and Geophysical Agency (Badan Meteorologi, Klimatologi, dan Geofisika)
C	Runoff Coefficient
ECOL	Ecological Dimension
ECO	Economic Dimension
K_s	Saturated Hydraulic Conductivity
MDS	Multidimensional Scaling
RAPFISH	Rapid Appraisal for Fisheries
RMS	Root Mean Square
RWH	Rainwater Harvesting
SB	Socio-Cultural Dimension
T	Technology Dimension
V	Harvested Rainwater Volume

Symbols

A	Effective catchment or infiltration area, m^2
C	Runoff coefficient (dimensionless)
dh/dl	Hydraulic gradient
K_s	Saturated hydraulic conductivity, m s^{-1}
Q	Water flow rate through soil, m^3 s^{-1}
R	Annual rainfall, mm $year^{-1}$
V	Harvested rainwater volume, L $year^{-1}$

Greek symbols

φ	Soil porosity