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# Plant-Soil Interlinkage Indicates Functional Green Water Areas in an Arid Ecosystem

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## ABSTRACT

The biodiversity of arid ecosystems is endangered due to environmental factors and human anthropogenic activities. Assessing green water areas and finding biological and ecological indicators is critical to conserving biodiversity. This study investigates the impact of annual plants in conserving green water areas and supporting the ecosystem. We explored the influence of soil conditions and annual plants on establishing and developing perennial shrubs from northern parts of Kuwait dominated by the *Rhanterium epapposum* community. The study plots comprise 25 vascular plants, with herbaceous plants dominating. The Simpson's reciprocal index for species-rich plots had the highest value of plant diversity (1/D = 14.9), while species-poor plots had the lowest (1/D = 7). Furthermore, *Rhanterium epapposum* from species-rich plots had the most significant structural values and canopy cover (42%), whereas species-poor plots represented only 8.4% cover. Soil characteristics such as phosphorus (>20%), nitrate (>42%), carbon (>10%), total organic carbon (>63%), and moisture content (>70%) were higher in species-rich plots. In addition, the PCA biplot correlation analysis between vegetation and soil parameters revealed that total organic carbon, nitrate, nitrite, and soil moisture content were the key variables in species-rich plots. We determined that arid areas with a significant number of annual plants are considered a biological indicator of green water areas. In addition, the presence of loamy soil texture is an ecological indicator of a healthy species-rich ecosystem. However, further research is necessary to understand the relationship between biotic and abiotic factors influencing the degree of elements present in green water areas.

**Keywords:** Biodiversity; Ecological indicator; Green water; Plant-soil interaction; *Rhanterium epapposum*

## INTRODUCTION

Overgrazing, land deterioration, desertification, and salinization are significant threats to desert sustainability, ecosystem services, and biodiversity (AbdelRahman, 2023). As a result, it is critical to investigate green water areas, their elements, how they impact the distribution of vegetation patterns, and the dynamics underlying plant-soil interlinkage. Falkenmark (1995) popularized the concept of green water (Falkenmark, 1995). Green water is precipitation retained on the soil surface but does not infiltrate or recharge aquifers (Falkenmark, 2008). According to Yang *et al*. (2015), green water areas are defined by vegetation and soils that aid in water absorption, infiltration, and storage. As a result, green water areas significantly impact plant biomass growth (Simiyu *et al*., 2022).

Furthermore, annual plants are significant in arid areas due to their rapid growth cycles and efficient resource utilization (Wheeler *et al.*, 2021). Plants have several traits that assist them in capturing and retaining water (Abdullah *et al.*, 2022a). Their quick growth and development allow for efficient water absorption, resulting in less water loss due to runoff. Plants that grow annually can also benefit from the occasional rainfall events in greenwater regions due to their deep, fibrous root systems, promoting water absorption (Schoonover and Crim, 2015). Their canopy structure can help deflect raindrops, reducing direct soil impact and improving water uptake.In contrast, annual plants are vital in nutrient cycling and soil fertility within green water areas (Furey and Tilman, 2021). Plants serve vital soil protection and stability functions in green water regions as they grow and establish plant cover. Their root systems bind soil particles together, reducing erosion risks caused by wind and water (Eldridge and Leys, 2003).

Soil physical and chemical qualities and vegetation diversity enhance green water areas and plant diversity. The texture, structure, and nutritional content of soil determine vegetation composition, growth, and water-holding capacity (Atkinson, 2018). On the other hand, soil properties should be nutritional, promoting adequate levels of nitrogen, potassium, phosphorus, magnesium, calcium, and other minerals, as well as sufficient organic matter to retain water and nutrients (Karlen *et al.*, 2001). Low amounts of one or more of these components would influence plant productivity. The variety of plants that can survive in each habitat is influenced by soil moisture levels, aeration, and nutrient availability (Jha *et al*., 1996). Additionally, other environmental factors such as temperature, precipitation patterns, and evapotranspiration rates significantly impact the distribution and composition of green water vegetation (Abbaspour *et al*., 2009).

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Although the concept of green water has recently been investigated, it has a substantial effect on biodiversity and soil in arid regions. Abdullah *et al*. (2022a) demonstrated that annual plant productivity is regulated in the spring following a decrease in winter temperatures. Furthermore, the duration and amount of rainfall received in November greatly impacted green water areas (Abdullah *et al.*, 2022a). Also, Alqallaf *et al.* (2020) observed that arid areas covered with annual grasses are excellent for green water storage for a lengthy period. Abdullah *et al.* (2021a) observed that soil characteristics were improved in regions with high annual density by supplying nearly 50% more soil moisture, phosphorus, organic matter, and carbon dioxide ($CO_2$) sequestration.

This study's primary purpose is to understand better the vital function of diversity and distribution of annual plants in preserving green water areas in arid ecosystems. The main objectives are as follows: 1) to determine the impact of annual plants on the *Rhanterium epapposum* community in green water areas, and 2) to investigate the physical and chemical qualities of the soil in species-rich and species-poor green water areas. The findings will help restoration managers and decision-makers choose sites for biodiversity conservation and ecological restoration and further understand the elements influencing the growth of native shrubs in desert ecosystems. In addition, this study will investigate the functions of annual plants in green water areas, including their contributions to plant-soil-water availability, nutrient cycling, and their influence on arid ecosystems.

## MATERIALS AND METHODS

### Study area

The fieldwork was conducted at the Al-Abdali protected site (estimated size 200,000 $m^2$), located in an agricultural area in the northern part of Kuwait City (29°58′15.68″ N and 47°50′29.94″ E). Kuwait is classified as an arid ecosystem, with lengthy hot and dry summers (average temperatures at their highest range from 42 to 46 °C), short, mild winters (average lowest temperatures range from 3 to 13 °C), and an average of 112 mm annual rainfall.

The site is characterized by an arid ecosystem dominated by a perennial native shrub, *Rhanterium epapposum* community, locally recognized as Kuwait's national flower. The area's topography generally appears flattened and smooth, with slight undulation. The field is entirely enclosed by a 2 m high fence comprising a diversity of naturally occurring native flora, represented by the *Rhanterium epapposum* community. The study area was divided into species-rich (SR), and species-poor (SP) plots based on previous work using Remote Sensing (RS) and Geographic Information System (GIS) techniques (Abdullah *et al.*, 2021a).

### Methodologies

This section details the field methods utilized for determining plant variabilities across SR and SP plots under the same environmental conditions, involving vegetation and soil survey, data collection, processing, and analysis. The investigation was carried out throughout multiple phases during early spring season (Jan-Feb 2019) to understand better the relationship between plant cover, floral diversity, and the physical and chemical aspects of the soil impacting the growth, development, and distribution of vegetation in each site. Figure (1) illustrates a detailed methodology workflow.

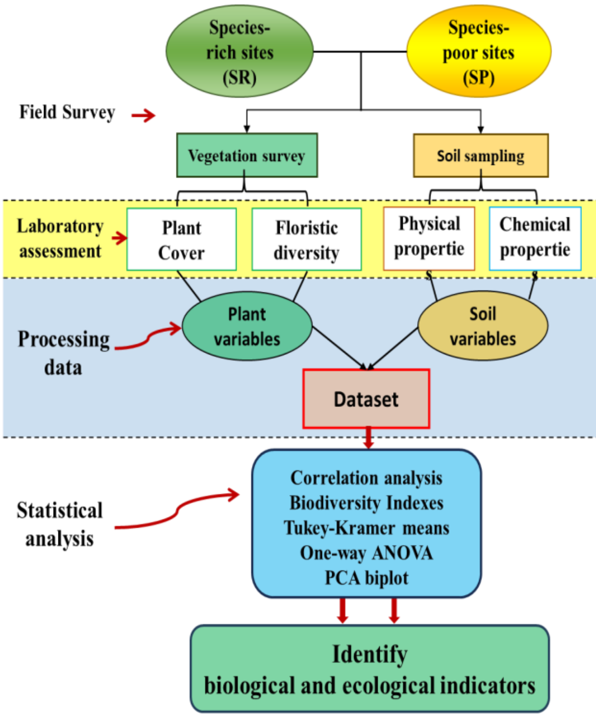


**Figure (1):** Methodology workflow for the current study to identify green water areas.

*Quantifying perennial plants*

For quantifying the total plant cover, represented by *Rhanterium epapposum* shrubs, 20 line-transects of length 50 m were conducted inside four plots of size 50 x 50 m (two plots representing each SR and SP sites). Measurements were made for each *Rhanterium epapposum*, shrub's height, and canopy size along the line-transects. Vegetation cover, frequency, and density were tabulated for further analysis.

*Quantifying annual plants*

The survey plots (50 x 50 m) are also utilized to quantify seasonal annual plants and study the floristic diversity in SR and SP sites. Thirty quadrats of size 1 x 1 m were randomly applied to measure each species' plant cover, frequency, and density following Barbour *et al.* (1987) and Daubenmire's (1959) cover class method. Also, refer to Abdullah and Al-Dosari (2022) for detailed information on the survey methods applied and the vegetation checklist of Kuwait.

*Soil sample collection and analysis*

Soil sampling was conducted to comprehend further the linkages between soil parameters and how these elements influence plant growth. Different soil depths were explored to understand the range of elements available at each location. A total of 36 soil samples were randomly obtained, with 18 samples representing soil surface (5 cm) and 18 samples representing subsoil surface (30 cm). The National Unit for Environmental Research and Services Laboratory at Kuwait University used international standard methods to test the soil samples for chemical and physical attributes (Burt, 2004). Electrical conductivity (EC), nitrite ($NO_2$-), nitrate ($NO_3$-), the potential of hydrogen (pH), total phosphorus ($P_{tot}$), total organic carbon ($C_{tot}$), carbon (C), solid particle, and soil moisture content were among the soil chemical characteristics studied. Furthermore, sand, silt, and clay were the key soil physical factors investigated.

*Biodiversity measures*

Biodiversity indices are calculated to study plant species composition and diversity differences at SR and SP plots. The calculated indices include species richness (S), evenness, Shannon-Weiner species index, Simpson's index (D), Simpson's index of diversity (1-D), and Simpson's reciprocal index (1/D). The calculated parameters were as follow:

$$S = \frac{N}{A}$$

Where: $S$, Species richness; $N$, Total number of different species observed and $A$, Total area surveyed.

Shannon-Weiner species diversity index (*H*) computed as:

$$H = -\Sigma p_i * ln(p_i)$$

Where: **Σ,** sum; *ln***,** natural log; and $\boldsymbol{p_i}$**,** the proportion of the entire community comprised of species i.

Simpson's index (*D*) computed as:

$$D = \frac{\Sigma n_i(n_i - 1)}{N(N-1)}$$

Where: n, is the number of individuals belonging to species I*;* and N, is the total number of individuals.

**Statistical correlation and analysis**

The extensive dataset generated from vegetation and soil analyses were subjected to statistical analyses. A one-way ANOVA test was performed on the dataset to identify significant differences ($p \leq 0.05$) between the SR and SP locations. Prior to the ANOVA, the Tukey-Kramer honestly significant difference (HSD) test was applied to confirm any significant differences between the variables. A bivariate Pearson correlation analysis was conducted to examine the linear relationship between plant heights and cover. Additionally, a Principal Component Analysis (PCA) biplot was utilized to assess the total variability in vegetation and soil data. All statistical analyses, including ANOVA, HSD, bivariate Pearson, and PCA biplot, were conducted using JMP® statistical software (SAS Institute, Inc., Cary, NC, version 17.2.0, 2023).

Green water areas with significant plant cover and species richness are more prominent in the SR plots compared to the SP plots. It is hypothesized that annual plants, which have a limited seasonal growth period, enhance the growth and development of Rhanterium epapposum shrubs by reducing evaporation from the soil surface and increasing the availability of moisture for plant uptake. If this hypothesis holds true, further analysis of the soil samples collected from the study plots will be conducted.

The chemical and physical properties of soil samples taken from the surface and subsoil layers in the SR and SP plots are expected to differ. If these differences are confirmed, this study will demonstrate a strong link between plant cover and soil characteristics. Specifically, soils with more extensive plant cover, including shrubs and herbs, are likely to exhibit richer qualities, such as higher organic matter content, greater nutrient availability, increased moisture retention, and a more varied grain size distribution.

## RESULTS

**Plant allometric parameters and floristic diversity analysis**

*Hypothesis 1:* In the species-rich (SR) plots, plant cover and species diversity are significantly higher compared to species-poor (SP) plots, with the assumption that annual plants contribute to the growth and development of *Rhanterium epapposum* shrubs. The results showed that *Rhanterium epapposum* cover was more significant in SR areas (42%) than in SP plots (8.4%) ($p \leq 0.002$, Tukey-Kramer mean). Furthermore, one-way ANOVA revealed highly significant differences in *Rhanterium epapposum* coverage across SR and SP plots ($p \leq 0.001$). Also, biodiversity indices of annual plants revealed greater diversity and plant cover in the SR plots.

As a result, annual plants provide organic matter, nutrients, and reduce soil moisture evaporation, stimulating the growth and development of the shrubs. Since the hypothesis was true, the collected soils' chemical and physical properties are further investigated.

*Vegetation structure and cover*

The results are summarized in Table (1) and Figure (2) shows that *Rhanterium epapposum* measurements varied throughout the study plots. Measurements from SR plots resulted in greater values (average of 76.1 cm length, 65.6 cm height; 42 % cover), while SP plots represented lower values (average of 34.6 cm length, 34 cm height; 8.4 % cover). Also, the bivariate Pearson analysis indicated a significant linear positive relationship ($R^2 = 0.76$; $p \leq 0.0001$) between *Rhanterium epapposum* heights and cover for all study plots (Figure 3).

*Floristic analysis*

Twenty-five vascular plant species belonging to 13 families were recorded in both plots, with herbaceous annual plants dominating (Table 2). The maximum number of species was 25; SR plots had the most significant number of plants and coverage, while SP plots only represented 12 sp. (Tables 2-3). The plant families Asteraceae and Fabaceae represented the most species, with 7 and 4 species, respectively. Grasses, *Stipellula capensis*, herbs, *Senecio glaucus*, *Launaea*

**Table (1):** Means comparison of *Rhanterium epapposum* measurements from species-rich and species-poor survey.

| Vegetation *Rhanterium epapposum* | Total species (n) | Parameters | length (cm) | height (cm) | Plant Cover (%) |
|---|---|---|---|---|---|
| | | Max | 90 | 73.3 | 50.4 |
| Species-rich sites | 25 | Average | 76.1* | 65.6** | 42* |
| | | Min | 62.2 | 58 | 33.6 |
| | | Max | 55.9 | 45.8 | 13.2 |
| Species-poor sites | 12 | Average | 34.6* | 34.0** | 8.4* |
| | | Min | 13.3 | 22.2 | 3.6 |

The mean data are statistically significant at the following levels: *$p \leq 0.002$ and **$p \leq 0.001$, determined using the Tukey-Kramer (HSD) test.

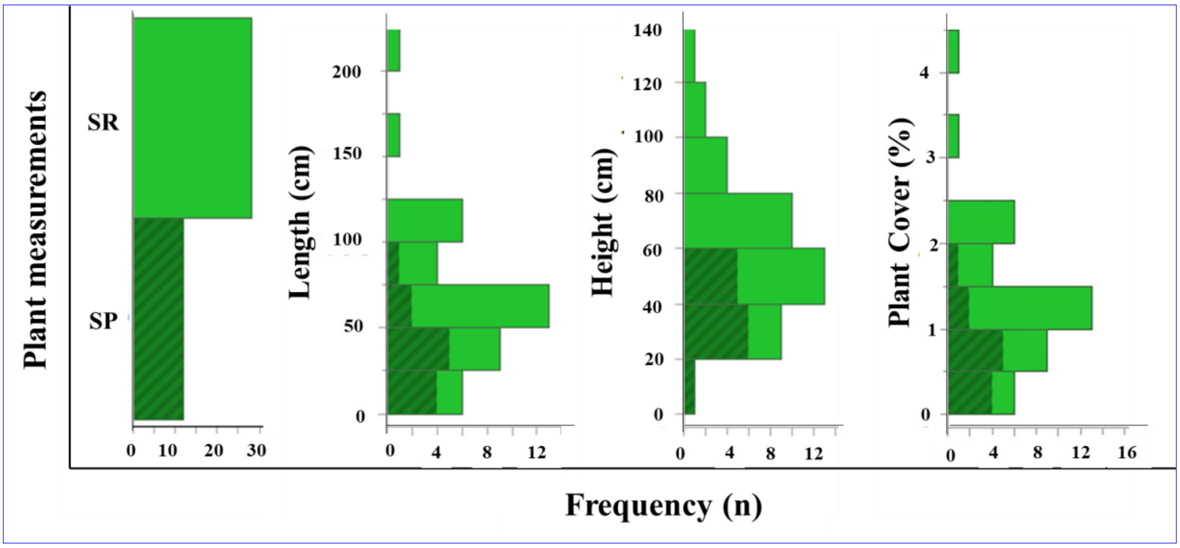


**Figure (2):** Density plots showing the distribution of *Rhanterium epapposum* measurements variation between species-rich (SR) and species-poor (SP) plots: length (cm), height (cm), and plant cover (%).

*nudicaulis*, and *Picris babylonica*, were the most prevalent plant species in both plots (Table 2).

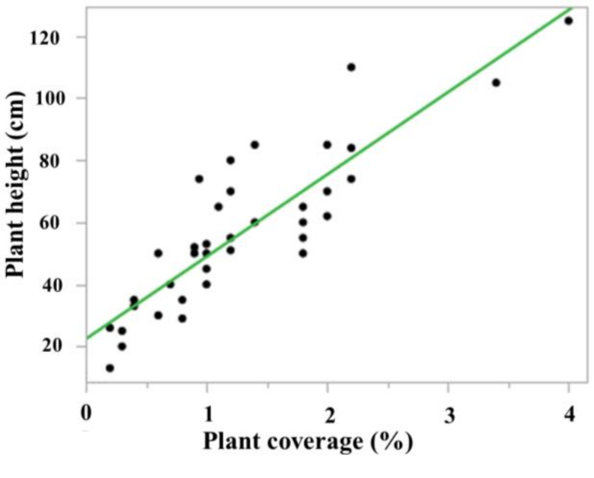


**Figure (3):** The bivariate Pearson analysis shows a significant linear relationship between *Rhanterium epapposum* heights (cm) and cover (%) for all study plots ($R^2 = 0.76$; $p \leq 0.0001$).

*Biodiversity measures*

For biodiversity, table (3) presents various biodiversity indices for two different plots, designated as SR and SP. These indices provide insights into the species richness, diversity, and evenness of plant communities in each plot.

*Species Richness (S)*

The SR plot exhibits significantly higher species richness, with 25 species identified. This suggests a more diverse plant community in this area. In contrast, the SP plot has only 12 species, indicating a lower level of biodiversity and potentially less ecological resilience.

*Simpson's Index (D)*

The Simpson's index for the SR plot is relatively low (0.067), suggesting that the community is not dominated by a few species, which is favorable for biodiversity. Meanwhile, the higher Simpson's index in the SP plot (0.142) indicates a greater dominance of certain species, which may reduce overall biodiversity.

*Simpson's Index of Diversity (1 - D)*

The SR plot shows a high Simpson's index of diversity (0.933), reflecting a well-distributed variety of species and a healthy ecosystem. The SP plot, while still showing diversity, has a lower index (0.858), suggesting a less balanced distribution of species.

*Simpson's Reciprocal Index (1/D)*

The SR plot's reciprocal index indicates a rich diversity of species (14.925), reinforcing the findings from the previous indices. However, in the SP plot has the lower value (7.042), suggesting that the community is less diverse (47% less diverse than the SR plots) and potentially more vulnerable to disturbances (Table 3).

**Table (2):** Vegetation composition and species distribution in *Rhanterium epapposum* community study plots: An analysis of annual plant species.

| Recorded Family | Species name | SR Plots | | SP Plots | |
|---|---|---|---|---|---|
| | | Freq (*n*) | Cover (%) † | Freq (*n*) | Cover (%) * |
| **Annual Herbs** | | | | | |
| Amaranthaceae | *Cornulaca aucheri* | 4.0 | 0.5 | 0.0 | 0.0 |
| Asphodelaceae | *Asphodelus tenuifolius* | 5.0 | 0.5 | 0.0 | 0.0 |
| Asteraceae | *Carduus pycnocephalus* | 3.0 | 0.5 | 2.0 | 0.0 |
| Asteraceae | *Ifloga spicata* | 15.0 | 3.0 | 13.0 | 3.0 |
| Asteraceae | *Koelpinia linearis* | 17.0 | 3.0 | 0.0 | 0.0 |
| Asteraceae | *Launaea nudicaulis* | 23.0 | 15.0 | 8.0 | 3.0 |
| Asteraceae | *Picris babylonica* | 21.0 | 15.0 | 5.0 | 0.5 |
| Asteraceae | *Reichardia tingitana* | 3.0 | 0.5 | 0.0 | 0.0 |
| Asteraceae | *Senecio glaucus* | 19.0 | 15.0 | 3.0 | 3.0 |
| Boraginaceae | *Arnebia decumbens* | 12.0 | 3.0 | 0.0 | 0.0 |
| Brassicaceae | *Brassica tournefortii* | 7.0 | 3.0 | 1.0 | 0.0 |
| Brassicaceae | *Savignya parviflora* | 5.0 | 0.5 | 0.0 | 0.0 |
| Caryophyllaceae | *Silene villosa* | 11.0 | 3.0 | 0.0 | 0.0 |
| Fabaceae | *Astragalus schimperi* | 6.0 | 0.5 | 0.0 | 0.0 |
| Fabaceae | *Astragalus spinosus* | 2.0 | 0.5 | 0.0 | 0.0 |
| Fabaceae | *Lotus halophilus* | 2.0 | 0.5 | 4.0 | 0.0 |
| Fabaceae | *Medicago laciniata* | 9.0 | 3.0 | 3.0 | 0.0 |
| Frankeniaceae | *Frankenia pulverulenta* | 7.0 | 0.5 | 0.0 | 0.0 |
| Neuradaceae | *Neurada procumbens* | 8.0 | 3.0 | 0.0 | 0.0 |
| Plantaginaceae | *Plantago boissieri* | 12.0 | 3.0 | 3.0 | 0.0 |
| Plantaginaceae | *Plantago ovata* | 10.0 | 3.0 | 4.0 | 0.0 |
| Polygonaceae | *Emex spinosus* | 5.0 | 0.5 | 0.0 | 0.0 |
| **Annual Parasite** | | | | | |
| Convolvulaceae | *Cuscuta planiflora* | 7.0 | 0.5 | 0.0 | 0.0 |
| **Annual Grass** | | | | | |
| Poaceae | *Stipellula capensis* | 37.0 | 15.0 | 14.0 | 3.0 |

†Cover class method following Barbour *et al.* (1987) and Daubenmire (1959).

*Shannon-Weiner Index (H)*

The Shannon-Weiner index for the SR plot indicates a high level of diversity (2.92), taking into account both species richness and evenness. The lower value (2.146) in the SP plot suggests reduced diversity, highlighting the ecological differences between the two plots.

*Evenness (E)*

The SR plot displays high evenness (0.919), indicating that species are relatively evenly distributed, which is beneficial for ecosystem stability. Although the SP plot has a slightly lower evenness (0.895), it still reflects a reasonably balanced distribution of species, but with less overall diversity. Generally, the biodiversity indices indicate that the SR plot supports a more diverse and balanced plant community compared to the SP plot (Fig. 4). The higher species richness, lower dominance, and greater evenness in the SR plot suggest a healthier ecosystem, which may be more resilient to environmental changes and disturbances. These findings could inform conservation strategies and management practices aimed at preserving biodiversity in these areas.

## Soil properties analysis

*Hypothesis 2*: The chemical and physical properties of soil derived from surface and subsurface of the study plots have different values assuming that SR plots deliver more organic matter, nutrients, moisture and variation in soil texture.

The results described in Table (4) and Figure (5), reveals that the chemical and physical variables of the soil differed significantly between the soil surface and

**Table (3):** Assessment of biodiversity indices in *Rhanterium epapposum* community: SR vs. SP plots.

| Measured biodiversity indices | Studied plots | |
|---|---|---|
| | SR values | SP values |
| Species richness (S) | 25.00 | 12.00 |
| Simpson's index (D) | 0.067 | 0.142 |
| Simpson's index of diversity (1 - D) | 0.933 | 0.858 |
| Simpson's reciprocal index (1/D) | 14.925 | 7.042 |
| Shannon-Weiner index (H) | 2.920 | 2.146 |
| Evenness (E) | 0.919 | 0.895 |

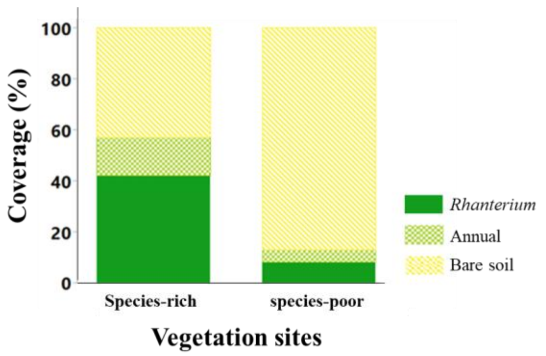


**Figure (4):** Density plots show *Rhanterium epapposum* composition and annual plant coverage (%) in species-rich and species-poor study plots.

soil subsurface across the investigated plots. Significantly higher values are found to be reflected mainly by SR plots, with subsurface soils having higher nutrient content than surface soils, as shown by phosphorus ($p \leq 0.03$), total organic carbon ($p \leq 0.02$), $NO_3^-$ ($p \leq 0.02$), $NO_2^-$ ($p \leq 0.001$), and moisture content ($p \leq 0.002$). In addition, hydrogen was substantially greater ($p \leq 0.001$) in SP soils (Table 4) and (Figure 5). In addition to the soil's chemical analysis, the physical texture of the soil was dominated by sandy loam soils, except for the subsurface soil of the SR plots, which had a loamy texture (richer in clay) (Table 4).

**Vegetation and soil analysis**

Biplot analysis explained 58.6% of the total variability for all study plots using two primary principal variables (component 1 and component 2). To facilitate graphical representation, vegetation and soil data were integrated into a single biplot graph (Figure 6). The PCA biplot for SR described the overall variation, revealing that $C_{tot}$, $NO_2$-, $NO_3$-, and soil moisture content were the key distinguishing variables (Figure 6).

The PCA biplot for SP revealed that EC, $NO_2$-, solid particles, and soil moisture content were the most differentiating factors (Figure 6). Plants from SR plots offer a significant amount of nutrients, soil organic matter, and soil moisture according to the PCA biplot analysis ($p < 0.0001$).

**Table (4):** Soil chemical and physical parameters of the 36 studied soil samples

| Parameters | Studied plots | | | |
|---|---|---|---|---|
| | Species-rich | | Species-poor | |
| | SR-S | SR-D | SP-S | SP-D |
| **pH** | 7.75 ± 0.049 [d] | 7.96 ± 0.049[d] | 7.75 ± 0.049[d] | 7.85 ± 0.049 |
| **EC (µmho/cm)** | 17.4 ± 3.65 | 12.94 ± 3.65[e] | 9.26 ± 3.65[e] | 24.1 ± 3.65 |
| **Moisture (%)** | 1.63 ± 0.41[b] | 3.96 ± 0.41[b] | 1.21 ± 0.41[b] | 2.75 ± 0.41 |
| **Hydrogen (%)** | 1.19 ± 0.008[a] | 1.19 ± 0.008 | 1.37 ± 0.008[a] | 1.37 ± 0.008[a] |
| **Soluble anions (mg/kg)** | | | | |
| **$P_{tot}$** | 146.95 ± 11.47[e] | 153.95 ± 11.47[e] | 133.48 ± 11.47[e] | 121.18 ± 11.47[e] |
| **$NO_3$-** | 0.031 ± 0.019[b] | 0.137 ± 0.019[b] | 0.031 ± 0.019[b] | 0.080 ± 0.019 |
| **$NO_2$-** | 1.59 ± 0.36 [c] | 3.48 ± 0.36[a] | 0.72 ± 0.36[a] | 2.23 ± 0.36[d] |
| **Organic Matter (%)** | | | | |
| **Total o. carbon** | 499 ± 252[d] | NA | 185 ± 370[d] | NA |
| **Organic carbon** | 1.95 ± 0.084 | 2.14 ± 0.084 | 1.88 ± 0.084 | 1.93 ± 0.084 |
| **Soil (%)** | 98.37 ± 0.41 | 96.04 ± 0.41 | 98.79 ± 0.41 | 97.24 ± 0.41 |
| **Soil texture (%)** | | | | |
| **Coarse sand** | 23 ± 6.4 | 12.95 ± 3.85 | 22 ± 3.00 | 25.5 ± 7.60 |
| **Fine sand** | 53.45 ± 1.95 | 37.35 ± 13.25 | 53.25 ± 11.35 | 47.05 ± 7.05 |
| **Silt** | 11.9 ± 5.00 | 28.25 ± 13.45 | 16.25 ± 12.35 | 14.55 ± 4.45 |
| **Clay** | 9.05 ± 2.05 | 18.7 ± 5.6 | 6.7 ± 3.20 | 8.85 ± 0.55 |

Analysis of variance showing soil properties means, standard error mean (SEM), and Interval range (minimum-maximum). Comparison using Tukey-Kramer (HSD) means with *p*-values: [a] $p \leq 0.001$, [b] $p \leq 0.002$, [c] $p \leq 0.003$, [d] $p \leq 0.02$, [e] $p \leq 0.03$; NA is not applicable. SR-D: species-rich subsoil, SR-S: species-rich surface soil, SP-D: species-rich subsurface soil; SP-S: species-rich surface soil.

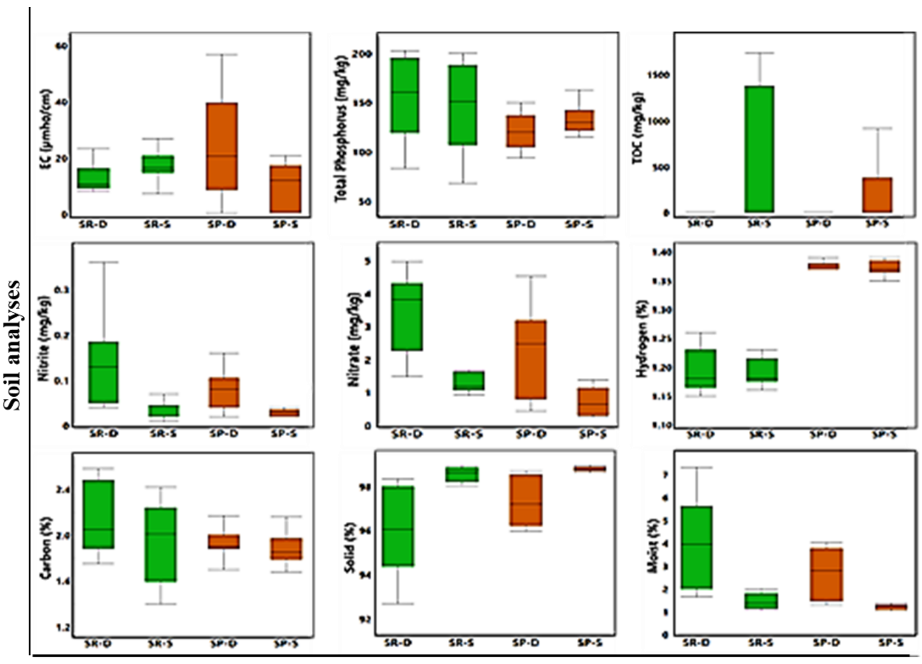


**Figure (5):** Plant diversity across different study plots in relation to physiochemical properties of analyzed soil. SR-D: species-rich subsurface soil, SR-S: species-rich surface soil, SP-D: species-poor subsurface soil; SP-S: species-poor surface soil.

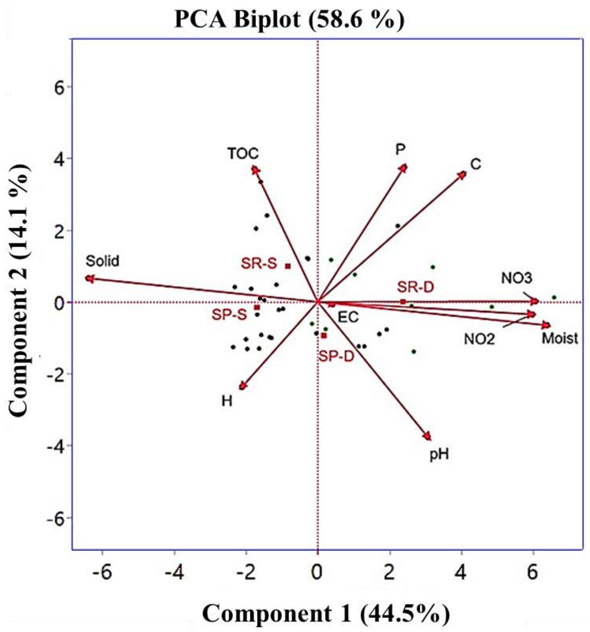


**Figure (6):** Principal Component Analysis (PCA) based biplot showing the correlation between studied plots and soil parameters ($p \leq 0.0001$). Studied plots: species-rich subsurface soil (SR-D), species-rich surface soil (SR-S); species-poor subsurface soil (SP-D); species-poor surface soil (SP-S). Soil parameters: Electrical conductivity (EC), nitrate ($NO_3^-$), nitrite ($NO_2^-$), the potential of hydrogen (pH), total phosphorus (P), total organic carbon (TOC), carbon (C), solid particle (Solid), and soil-moisture content (Moist).

## DISCUSSION

### The role of annual plants in supporting green water areas

These findings demonstrate that annual plants are beneficial in improving soil characteristics, which is critical in arid ecosystems. The frequency, cover, and diversity of annual plants surrounding the shrubs also significantly stimulated the shrub canopy cover of *Rhanterium epapposum*. Abdullah *et al.* (2021b) observed similar results; however, they utilized Remote Sensing (RS) and unmanned aerial vehicles (UAVs)-based technologies to evaluate the vegetation biomass and carbon stock. This study is an example of a conventional ecological field survey in which actual measurements of floristic diversity, composition, and plant cover are used to acquire an in-depth understanding of vegetation patterns and their interactions with soil conditions.

Brown (2003) presented a model evaluating the shifting phase of *Rhanterium epapposum* shrubs to *Haloxylon* community in northern parts of Kuwait. He demonstrated that the succession of annuals could lead to healthy perennial shrub communities forced by various environmental conditions, including soil properties (Brown, 2003). Based on our findings, we developed a schematic diagram of a conceptual model to define the role of annual plants as a biological indicator in enhancing the soil properties and stimulating the growth and development of perennial shrubs in green water areas (Figure 7).

It is found that plant diversity and cover (47 %) were more significant in SR plots surrounding the shrubs than SP plots. *Rhanterium epapposum* shrubs surrounded by high cover of annual plants had larger structures with significantly higher canopy cover (averaged 65.6 cm in height, $p \leq 0.001$), about twice the heights of shrubs from SP plots (averaged 34 cm in height, $p \leq 0.001$). The size of the shrubs was related to the increase in soil moisture content (> 70 %), $P_{tot}$ (> 20 %), and total organic carbon (> 63 %) availability in the soil. The increase in soil moisture in SR plots is likely related to the density and diversity of annual species covering the soil surface, which decreases the evapotranspiration rate and holds more water in the subsoil surface for root uptake (Zhang *et al.*, 2001). Due to their quick life cycle, annual plants play an essential role in increasing nutrients and organic matter in the soil by decomposition at the end of their life cycle (Figure 7). Increasing soil nutrients from the decaying process is essential for improving soil fertility and aiding in future seed germination.

Asteraceae and Fabaceae were the most abundant plant families in the study plots. It was found by Chen *et al.* (2015) that three species of Asteraceae significantly increased the soil's total phosphorus and total nitrogen content (Chen *et al.*, 2015).

Like our case, Asteraceae's species diversity and plant cover in SR plots showed great values of total phosphorus (> 20 %). Likewise, plants of the Fabaceae have a unique symbiotic role with nitrogen-fixing soil bacteria and specialized structures (nodules) in their roots that house Rhizobium bacteria (Maróti and Kondorosi, 2014). Also, Poaceae grasses were abundant in our plots by a single annual plant, *Stipellula capensis,* with greater density in SR plots. Generally, grasses are known to increase soil fertility by decomposing their fibrous roots to create organic matter, improve the structure of the soil, and help rebuild topsoil (Guo *et al.*, 2021). In addition, grasses can control soil erosion due to their rapid seasonal growth (Duan *et al.*, 2022).

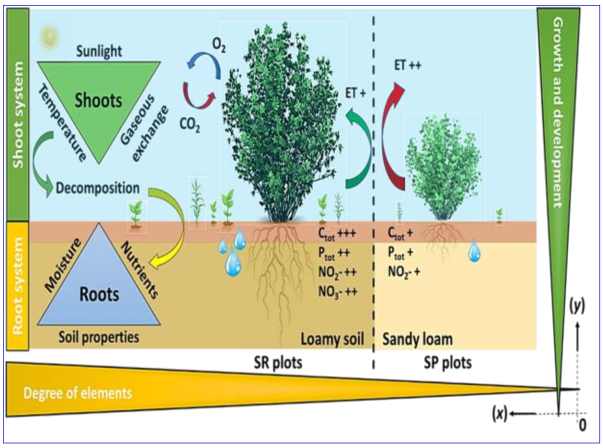


**Figure (7):** A conceptual model of green water areas illustrating the critical role of annual plants and the range of soil elements in promoting the growth and development of perennial shrubs. Total organic carbon (Ctot), Total phosphorus (Ptot), nitrite ($NO_2^-$), nitrate ($NO_3^-$), and evapotranspiration (ET). Low value (+), medium value (++), and high value (+++). As the degree of elements (i.e., nutrients, soil properties, moisture) increase on the X-axis, plant diversity and growth increase on the Y-axis.

**The role of soil properties in supporting green water plants**

The soil is vital for plants to maintain a healthy growing environment in green water areas. The level of soil compaction, infiltration rate, and water-holding capacity directly influence plants' growth and development (Al-Awadhi *et al.*, 2003; Al-Dousari *et al.*, 2019; Abdullah *et al.*, 2021b). Soil pH values were relatively similar in this study, with soil surface pH of 7.79 and slightly alkaline in the subsoils, pH of 7.85-7.96. Also, the results showed similar soil texture throughout the plots, represented by sandy loam texture, except for the subsoils of SR plots, represented by loamy texture. Sandy loam soils are not ideal for arid plants since they can quickly drain excess water but cannot hold significant amounts of water or nutrients for plants (Huang and Hartemink, 2020). Loamy soil is known best for plant growth as it has a high water-holding capacity by retaining water and nutrients required for plant growth (Dodd and Lauenroth, 1997; Asadalla *et al.*, 2021).

By highlighting the adaptability of plant species to water-stressed conditions and their influence on soil properties, the findings underscore the necessity of integrating plant-soil interactions into the management and conservation strategies of arid landscapes. Furthermore, the research points to the importance of preserving these green water areas not only for their ecological roles but also for their potential in mitigating the impacts of climate change and enhancing resilience against environmental degradation. The presence of loamy soils illustrates why plants at SR plots have a more prosperous composition of plants with significant canopy coverage of annuals and shrubs. Therefore, according to our investigation, loamy soil textures in arid regions should be considered an ecological indicator for their significant ability to support plants.

**Green water areas as an indicator of a functioning arid ecosystem**

It is critical to thoroughly understand and predict the effects of driving variables to manage dry lands quickly and efficiently. According to our findings, annual plants and soil properties critically support the growth and development of native desert ecosystems. The diversity of annual plants could be utilized to indicate a healthy ecosystem maintained by suitable soil qualities (Ndiaye *et al.*, 2000; Li *et al.*, 2014). Furthermore, our results showed that SR plots have increased ecosystem performance due to dense vegetation (53% diversified) and increased soil property values. In contrast, SP areas have reduced diversity and lower soil qualities.

Moreover, plants provide organic matter in leaf litter, boosting soil fertility and nutrient cycling (Knops, 2002). As represented by SR plots, the density of annuals offers more leaf litter, indicating an excellent decomposition process and more nutrients retained in the soil. Also, the amount of plant cover and litter deposits provide a protective barrier (like mulches) that limits soil loss and encourages soil aggregation. Also, with their various microbial communities, soils aid in decomposition and mineralization, allowing plants to access nutrients (Heijboer *et al.*, 2016). Our findings suggest that the diversity and distribution of annual plants can serve as a biological indication of green water conservation in desert ecosystems, as they provide critical support for recovering perennial plants.

## CONCLUSION

The investigation into plant-soil interlinkages in arid ecosystems reveals critical insights into the functioning of green water areas and their significance in maintaining ecological balance. This study demonstrates that the complicated relationships between vegetation and soil moisture dynamics play a crucial role in defining functional green water zones, which are essential for sustaining biodiversity and ecosystem services in these harsh environments. This study investigates various components, including a field survey, vegetation distribution (both annuals and perennials), plant cover, and soil properties, to underscore the significance of green water areas in arid ecosystems. The presence of annual plants and loamy soil texture serves as biological and ecological indicators of a healthy ecosystem that supports the growth of plants adapted to arid conditions. However, further research is necessary to understand the relationship between biological soil crust (biocrusts), microbial communities (i.e., cyanobacteria and algae), and soil nutrient levels, all of which influence the growth and development of plants. In addition, understanding the responses of annual plants to altered precipitation patterns, temperature shifts, and altering biological dynamics is critical for managing green water areas in a changing climate.

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# ترابط النبات والتربة يشير إلى مناطق المياه الخضراء الوظيفية في نظام بيئي جاف

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## الملخص العربي

يعد التنوع البيولوجي في النظم البيئية القاحلة مهددا بالانقراض بسبب العوامل البيئية والأنشطة البشرية، كما أن تقييم مناطق المياه الخضراء وإيجاد المؤشرات البيولوجية والإيكولوجية أمر بالغ الأهمية للحفاظ على التنوع البيولوجي. حيث تبحث هذه الدراسة تأثير النباتات الموسمية في الحفاظ على مناطق المياه الخضراء ودعم النظام البيئي. كما بحثنا في تأثير ظروف التربة والنباتات الموسمية على نمو و استقرار الشجيرات المعمرة في المناطق الشمالية للكويت والتي يهيمن عليها مجتمع *Rhanterium epapposum*. وجدنا في منطقة الدراسة 25 نوع من النباتات اللاوعائية، وحقق مؤشر سيمبسون التبادلي للمناطق الغنية بالأنواع أعلى قيمة للتنوع النباتي (D/1 = 14.9)، في حين أن الأراضي الفقيرة بالتنوع كانت الأقل (D/1 = 7). حصل *Rhanterium epapposum* في المناطق الغنية بالأنواع على أكبر نسبة للغطاء النباتي (42%)، عكس الأراضي الفقيرة نسبة 8.4% فقط من الغطاء. بينما تمثل خصائص التربة مثل الفوسفور (< 20%)، النترات (< 42%)، الكربون (< 10%)، إجمالي الكربون العضوي (< 63%)، وكانت نسبة الرطوبة (< 70%) في الأراضي الغنية بالأنواع. كشف تحليل الارتباط الثنائي بين الغطاء النباتي ومعايير التربة أن إجمالي الكربون العضوي، والنترات، والنتريت، ومحتوى رطوبة التربة من المتغيرات الرئيسية في الأراضي الغنية بالأنواع، ووجدنا أن المناطق القاحلة التي تضم عددا كبيرا من النباتات الموسمية تعتبر مؤشرا بيولوجيا لمناطق المياه الخضراء. ويعد وجود نوع التربة (loamy soil) مؤشرا ايكولوجيا على النظام البيئي الغني بالأنواع. من الضروري في المستقبل إجراء المزيد من الأبحاث لفهم العلاقة بين العوامل الحيوية والعوامل الغير حيوية التي تؤثر على العناصر الموجودة في مناطق المياه الخضراء.