Adaptation and ecophysiological responses of Sidr (*Ziziphus spina-christi*) to different ecological conditions: application studies on Al-Baha region, Saudi Arabia

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**Abstract**

The important aspect of plant physiological ecology studies in the context of the Earth-system was approaching plants as complex systems. This kind of approach allowed a better understands of responses of plants in relation to the environmental conditions. This work reports ecophysiological studies on the Sidr tree of Al-Baha in an attempt to elucidate its morphological and physiological features that account for their survival on the sites under study. Three visually similar Sidr trees, one from each of three ecologically different locations namely Khitan, Aqiq, and Makhwah were selected for this study. Soil characterizations including relative water content and salinity were measured. Physiological parameters including stomata length, width and number, epicuticular wax content, and relative leaf water content (RWC), were measured. All results were analyzed statistically by Statistix 1.0 software. Very few studies have addressed the ecophysiological responses of Sidr (*Ziziphus spina-christi*) to different ecological conditions. For the first time, study of soil water parameters, and leaf, and stomata physiological parameters of the Sidr tree reflected the adaptation of the tree to the three different ecological conditions in Al-Baha region, and accounted for its survival on the sites under study.

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Introduction

Sidr (Ziziphus spina-christi) grows in a wide range of habitats from northwest Africa into the eastern Mediterranean, the Arabian Peninsula and western and tropical Asia (Kuden, 2013) and naturally occurs in sixteen African and thirteen Asian countries (Scholte et al., 1991). It is one of the most drought and heat tolerant plant species growing at altitudes from 0 to 2000 masl. The tree is widely used to produce a range of products: food, fodder, fuel, drink, timber, medicine and as a shade tree and to protect against soil erosion (Orwa et al., 2009). Ziziphus spina-christi is an important source of choice grade and expensive honey particularly in the Middle East (Adgaba et al., 2013). It is an important cultivated tree and one of the few truly native tree species of Saudi Arabia that is still growing along with many newly introduced exotic plants (Saied et al., 2008).

The species occurs widely, in several southwestern valleys of Saudi Arabia where the fruit, leaves and even the bark of the tree are extensively eaten by livestock (goat, sheep and camel). A wild, thorny, shrub-like tree that grows in desert area where ground water accumulates. According to legend cited even in Muslim sources, it is believed to be the tree of which Christ’s crown of thorns was made. A member of the Buckthorn family, it is found in Najd, in the northern and eastern parts of Saudi Arabia. The tree, when cultivated, bears good fruit and is often thornless. The fruits, resembling mini-apples, are sold in local markets in Saudi Arabia and Bahrain. Sidr tree leaf powder has long been used in Islam to wash bodies of the dead. Its dried and powdered leaves, mixed with hot water, are also used by women as a hair wash which makes the hair soft and lustrous. Mandavillae (1990) reports trying it and found it “very effective as a shampoo”. The leaves are also used to treat dandruff, counter obesity, and to clean the body. Its traditional medicinal uses also include as a stomachic, an appetizer, an astringent and a cough medicine. In the Asir region of southwestern Saudi Arabia, a decoction is made from Sidr (Ghazanfar, 1994).

The Sidr tree (Christ’s Thorn Jujube) belong to the family Rhamnaceae. It differs widely in distribution relative to the availability of water, but most are well adapted to xeric sites. It grows naturally in the Arabian Peninsula, and planted widely in the tropics and subtropics (Ghazanfar, 1994). The tree grows widely in Al-Baha region, especially in Al Khitan, Al Aqiq, and Al Makhwah regions that represent three different ecological conditions.

The tree is voracious, fast-growing, medium-to large-sized, evergreen cylindrical shape, with branches hanging, and a whole deep root. The tree scatters many shades and a height of between three to ten meters, branches spread out and pendant and contains small spines with different density. The Sidr tree needs warm winter, and cannot withstand low temperatures and generally buckthorn trees grow in warm and temperate regions. The tree is drought-tolerant and grows in all types of land ranging from condition of high water table to sandy soil or yellow (Ghazanfar, 1994).

In general, plants responds to lack of water by halting growth and reducing photosynthesis and other plant processes in order to reduce water use. Some species have anatomical or physiological characteristics that allow them to acclimate to environments. All plants exhibit higher stomata closure under xeric than dry habitats, and have a waxy coating on their leaves called “cuticle” but some species have developed exceptionally thick cuticles and epicuticular wax that reduce the amount of water lost by evaporation from the leaf surface. Leaf hairs, which reduce air movement at the leaf surface, are another means of reducing evaporation from the leaf (Hillel, 2000). Leaves showing greater stomata density and leaf thickness and smaller guard cells than others, are able to enhance water use efficiency defined as CO₂ gained/water lost (Bidwell, 1974).

Since the amount of surface area exposed to the atmosphere affects evaporation, leaf size and thickness are other adaptations, with thicker leaves and smaller leaves being more resistant to water loss. Some species have evolved large surface root systems to quickly absorb rainfall, while other species grow
deep root systems to tap deep water tables. Some plants avoid water scarcity by dropping their leaves and quickly re-growing new leaves when environmental conditions improve.

In general, as water loss progresses, leaves of some plant species may appear to change color, usually to blue-green. Drought symptoms resemble salt stress because high concentrations of salts in the root zone cause water loss from roots. Aside from the moisture content of the soil, environmental conditions of high light intensity, high temperature, low relative humidity and high wind speed will significantly increase plant water loss. The prior environment of a plant also can influence the development of water stress (Knox and Lehtola, 2005).

Tree leaves differ in tissue elasticity, that may result from changes in nutrient status, osmotic and pressure potentials, tissue maturity, soil water content, etc. (Correia et al., 1989). Both high and low tissue elasticity may contribute to desiccation tolerance under different environmental conditions (Roberts et al., 1980). In tissue of low elasticity, water potential would rapidly decrease with a given change in water content. Highly elastic tissue can withstand greater changes in cell volume during dehydration and maintain higher pressure potential.

Soil salinity is a severe environmental hazard that impacts the growth of many plants, and affects the soil physical and chemical properties, and the water availability to plants. This relates to an increase in osmotically active solutes per cell, passive concentration of existing solutes by a reduction in cell size, or a redistribution of osmotically active water from the symplasm to apoplasm (Tyree and Jarvis, 1982).

Very few studies have addressed the ecophysiological responses of Sidr (Ziziphus spina-christi) to different ecological conditions. For the first time, this work reports eco-physiological studies on the Sidr tree of Al-Baha in an attempt to elucidate its morphological and physiological features that account for their survival on the sites under study.

Materials and methods
Plant samples
The study areas were located in the Al-Baha region in Southwestern Saudi Arabia (Fig. 1). Three visually similar Sidr trees, one from each of three ecologically different locations namely Khitan, Aqiq and Makhwah (Fig. 2).

Field site description
This research was conducted in in three different ecological conditions in Al-Baha region including the Khitan, Aqiq, and Makhwah regions. As shown in Table 1, Khitan is flooded lowland valley about 70 masl, located 41°45′ N and 19°20′ E, and has a worm in winter, hot in summer and an annual rain fall ranging from 100 to 250 mm. Aqiq, is a wet area about 1540 masl, located 20°30′ N and 41°20′ E, and has a Mild cold in winter, moderate in summer and an annual rain fall ranging from 229 to 581 mm. Makhwah is moist-dry lowland about 45 masl, located 41°45′ N and 19°20′ E, and has a Mild cold in winter, hot in summer and an annual rain fall ranging from 100 to 250 mm.

Khitan is an ancient valley located in Al-Baha area in the part of Tehama, and extends for more than twenty kilometers to the valley area. Extends through the valley, the mountain range of Sarwat, which begins from Aqaba through to Hejaz, and it end of the Strait of Bab el Mandeb. The valley consists of a variety of geographical landmarks, and various forms of terrain. High, and the most prominent of these valleys and
valley ten (annexation Shin) that lies in Awamer the wing next to the village, which is now being the establishment of a large hydro dam Sakhadd both valleys in the future. The climate of Khitan Valley is different from that of Al-Baha, in spite of the proximity between them (approx. 25 km); where the high temperature in summer and warm in winter and mild in the spring. Generally considered the climate of the valley within the region dry but cool winter climate, beautiful queer in the rest of the seasons of the year. Humidity range is between 52% to 67% and atmospheric pressure between 602 to 607 and the average temperature is 32°C and 18 major micro class, ranging rainfall in the valley between 100 mm to 250 mm per year.

Aqiq is located in the north-east of the city of Al-Baha between longitudes 20 - 20.30 degrees North, and latitude 41.30 - 42 degrees East longitude. Away from Al-Baha area of about 45 km and rises from sea level at about 1540 m. In the mountain areas, Aqiq is featured by a mild cold climate in winter and moderate climate in summer. In Tehama the summer is hot, and the winter is mild cold. The difference formations terrain affects the climate of the region. The Sarwat sector is exposed to fronts air moist come from Tehama. This consists clouds and fog often expose Sarwat to drag and fog coming from the Red Sea in winter. These air masses, thunderstorms and declining temperatures expose the region to heavy rains in queer characterized by a mild climate in spring and summer. The climate of Tehama sector is different from Sarwat sector; despite the proximity between the two sectors (25 km). Tehama is undulating coastal plains high temperature in summer and warm in winter and moderate in the spring. In general Aqiq is considered within the dry region, but cool winter climate, beautiful queer in the rest of the seasons of the year. Humidity range in the region of 52% to 67% and atmospheric pressure between 602 to 607, with an average temperature of 23°C of the highest and 12°C of the lowest, and rainfall ranges in Sarwat between 229 mm to 581 mm, whereas In Tehama sector between 100 mm to 250 mm annually.

Makhwah is in the Southwest of Al-Baha area at the Tehama area at a latitude of 19 - 20 and longitude 41–45 in the embrace of the mountains Sarwat surrounded by mountains on all sides, from the East and North Sarwat mountains and from the West is lower and upper Shada mountain, and from South are Nasbah and Mesouda mountains. Makhwah is away from the capital of the region (Al-Baha) by 45 km and with which it has several roads which is confined to the South plains of the coastal region and this will be the nature of the joint between the valley and the mountain, and the farthest point between them to the Red Sea does not exceed 60 km. Makhwah climate is hot in summer so that the temperature reaches 42°C in the winter is mild and considered Machta for the people of the highlands. Makhwah rises to maintain the level of 400 m above sea level and rainfall ranges in Tehama between 100 mm to 250 mm annually.

Measuring soil relative water content
Soil relative water content was determined as described by Anderson and Ingram (1993), on dry weight basis. Three samples each of 50 g, weighing, then dried at a constant weight at 105°C. The dry weight was recorded and the moisture content by [(Sample wet weight – Oven dry weight) / Oven dry weight] x 100.

Soil salinity
Surface soil (0–15 cm) salinity was measured in triplicates under laboratory conditions using a salinometer, and measured by ds.m⁻¹, essentially as described by Hussain and Al-Hawas (2008).

Assessment of physiological parameters
Physiological parameters including stomata length, width and number, epicuticular wax content, and relative leaf water content (RWC), were measured.

Leaf surface area
Five representative leaves were sampled from different levels of the canopy of each the three trees. Leaf surface area was measured as described by
Pandey and Singh (2011). Leaves of each tree were spread over millimeter graph paper, and the outline of leaf was drawn. The leaf area was measured by cutting the area of the millimeter graph paper covered by the outline and weighing the cuts on an electronic three digit balance. One cm² of the same millimeter graph paper was also cut and weighed. Leaves of were sampled thrice. The following equation was used to calculate the leaf area nondestructively: Leaf area (cm²) = x / y, where x is the weight of the graph paper covered by the leaf outline (g) and y is the weight (g), of the cm² area of the graph paper.

Leaf epicuticular wax
Epicuticular waxes were estimated from the outermost fresh leaves following methodology of O’Neal et al. (2002). As the stage of plant maturity are thought to influence epicuticular wax content, the leaves of similar age were taken and washed in n-hexane for 1 min. The n-hexane extracts were filtered and dried in order to calculate weight of wax. All the results of epicuticular wax represent averages of triplicate determinations and are expressed on a μg.cm⁻² leaf area.

Leaf relative water content
Leaf RWC was determined by excising 10 leaves, weighed, and then re-weighted after floated on distilled water for 24 hours, oven drying at 80°C to get the dry weight. RWC = (FW – DW) / (TW – DW) where FW = leaf fresh weight, DW = dry weight and TW = turgid weight (Muquing and Ru-Kai, 1998).

Stomata parameters
Stomata length, width and number, were measured following nail paint peeling technique as described by (Capellades et al., 1990), by applying cellulose acetate (clear nail polish), to the upper leaf surface, which was peeled and examined microscopically for length (μ), width (μ) and number per mm² of stomata.

Statistical analysis
Statistical analysis was carried out using Statistix 1.0 for Windows software (Analytical Software, Tallahassee FL).

Results and discussion
Adaptation of the Sidr tree to those three different ecological conditions of Al Khitan, Al Aqiq, and Al Makhwah in Al-Baha region can be reflected on the morphological and physiological features of the tree, and account for its survival on the sites under study. The study of soil parameters, water content and salinity, revealed significant differences (p ≥ 0.05) across the three locations (Fig. 3), but not in a trendy fashion; confirming distinct difference among the three ecological location under study.

Table 1. Summary of the characteristics of Khitan, Aqiq, and Makhwah regions in Al-Baha region.

<table>
<thead>
<tr>
<th>Region</th>
<th>Rainfall Lowest</th>
<th>Rainfall Highest</th>
<th>Location Longitude ° North</th>
<th>Location Latitude ° East</th>
<th>Altitude (masl)</th>
<th>Distance from Al-Baha (Km)</th>
<th>Climate</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Khitan</td>
<td>100</td>
<td>250</td>
<td>41–45</td>
<td>19–20</td>
<td>70</td>
<td>25</td>
<td>Worm in winter, and hot in summer</td>
<td>Flooded</td>
</tr>
<tr>
<td>Aqiq</td>
<td>229</td>
<td>581</td>
<td>20 20.30</td>
<td>41.30–42</td>
<td>1540</td>
<td>45</td>
<td>Mild cold in winter, and Wet moderate in summer</td>
<td>Wet</td>
</tr>
<tr>
<td>Makhwah</td>
<td>100</td>
<td>250</td>
<td>41–45</td>
<td>19–20</td>
<td>400</td>
<td>45</td>
<td>Mild cold in winter, and hot Moist/Dry in summer</td>
<td>Moist/Dry</td>
</tr>
</tbody>
</table>

Stomata parameters, length, width, and number, varied significantly (p ≥ 0.05) across the three locations (Fig. 4), and showed a trendy fashion. This result confirms adaptive characteristics of stomata features to survive under different ecological conditions, and water availability. The tree of Makhwah under the moist/dry conditions have acclimatized to its environment by exhibiting higher stomata closure and has a greater epicuticular wax coating than that under wet or flooded habitats (Fig. 5). These features reduce the amount of water loss by evaporation from the leaf surface.
Table 2. Profiles of Sidr leaf physiological and underneath soil characteristics in three different ecological conditions in Al-Baha region.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Makhwah (Water +++ )</th>
<th>Aqiq (Water ++ )</th>
<th>Khitan (Water + )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean ± SD</td>
<td>Mean ± SD</td>
<td>Mean ± SD</td>
<td></td>
</tr>
<tr>
<td>Soil</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water Content (%)</td>
<td>32 ± 0.36</td>
<td>25.5 ± 0.62</td>
<td>18.1 ± 0.2</td>
</tr>
<tr>
<td>Salinity (ds.ml-1)</td>
<td>54.67 ± 0.58</td>
<td>17.67 ± 0.58</td>
<td>27.33 ± 0.58</td>
</tr>
<tr>
<td>Stomata</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length (µm)</td>
<td>32.3 ± 0.79</td>
<td>34.2 ± 0.36</td>
<td>36.63 ± 0.55</td>
</tr>
<tr>
<td>Width (µm)</td>
<td>16.4 ± 0.46</td>
<td>13.87 ± 0.15</td>
<td>12.67 ± 0.40</td>
</tr>
<tr>
<td>Number (no.mm-2)</td>
<td>222.33 ± 5.86</td>
<td>183.67 ± 6.66</td>
<td>153.00 ± 3.61</td>
</tr>
<tr>
<td>Leaf</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Epicuticular Wax Content (µg cm-2)</td>
<td>0.91 ± 0.01</td>
<td>1.30 ± 0.02</td>
<td>2.27 ± 0.06</td>
</tr>
<tr>
<td>Surface Area (cm^2)</td>
<td>40.63 ± 0.65</td>
<td>19.34 ± 0.86</td>
<td>13.77 ± 0.46</td>
</tr>
<tr>
<td>Water Content (%)</td>
<td>72.60 ± 2.55</td>
<td>54.49 ± 3.05</td>
<td>40.77 ± 0.78</td>
</tr>
</tbody>
</table>

Table 3. Correlation matrix of measured parameters.

<table>
<thead>
<tr>
<th>Correlation Matrix</th>
<th>Epicuticular Wax Content (µg/cm²)</th>
<th>Leaf Surface Area (cm²)</th>
<th>Leaf Water Content (%)</th>
<th>Soil Salinity (ds.ml⁻¹)</th>
<th>Soil Water Content (%)</th>
<th>Stomata Length (µm)</th>
<th>Stomata Number (no.mm⁻²)</th>
<th>Stomata Width (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epicuticular Wax Content (µg/cm²)</td>
<td>-0.85</td>
<td>-0.95</td>
<td>-0.53</td>
<td>-0.98</td>
<td>0.99</td>
<td>-0.95</td>
<td>-0.91</td>
<td></td>
</tr>
<tr>
<td>Leaf Surface Area (cm²)</td>
<td>0.97</td>
<td>0.90</td>
<td>0.93</td>
<td>-0.92</td>
<td>0.97</td>
<td>0.99</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>Leaf Water Content (%)</td>
<td>0.77</td>
<td>0.99</td>
<td>0.99</td>
<td>-0.99</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>Soil Salinity (ds.ml⁻¹)</td>
<td>0.69</td>
<td>-0.66</td>
<td>0.76</td>
<td>0.84</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil Water Content (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stomata Length (µm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stomata Number (no.mm⁻²)</td>
<td>-0.99</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.99</td>
</tr>
<tr>
<td>Stomata Width (µm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Leaf parameters, epicuticular wax thickness, leaf surface area, and leaf water content, varied significantly (p ≥ 0.05) across the three locations (Fig. 6), and showed a trendy fashion. This result confirms adaptive characteristics of leaf structure to survive under different ecological conditions, and water availability. Leaves exhibited a decline in surface area and content of epicuticular wax with the lessening of available water in the soil beneath trees (Fig. 7). Since the amount of leaf surface area exposed to the atmosphere affects evaporation, leaf size and thickness are other adaptations, with thicker and smaller leaves being more resistant to water loss. Leaf color is shown to change in the different ecological sites; leaves appeared to blue-green as soil water content becomes lesser (Fig. 7).
water content showed strong negative correlation with epicuticular wax thickness (-0.95). This indicates the increase in soil water content is associated with larger leaves and decreased epicuticular wax content. Leaf wilt and fall appeared to have occurred to reduce water loss (Fig. 8).

As shown in Table 3, soil water content (%) showed strong positive correlation with stomata width (0.97), and stomata number (0.99) and, on the contrary, strong negative correlation with stomata length (-0.99). This indicates that the increase in soil water content is associated with larger stomata size and greater stomata density, and the tree responded to the lack of water by reducing stomata size and density in order to reduce water loss.

Soil salinity was significantly (p ≥ 0.05) different among the three locations. Depending upon different soil salinity, mean soil salinity ranged between 54.67 ± 0.58 and 17.67 ± 0.58 ds.m⁻¹ in the surface 0–15 cm (Table 2), with soil salinity being significantly higher in the soil of Khitan valley due to mountain wash.

Despite high salt stress resample drought because high concentrations of salts in the root zone cause water loss from roots, the tree grown in abundance of water and significantly higher salinity in Khitan did not demonstrate drought suffering. The increase in soil salinity, the higher the osmotic potential and hence reduced cell and leaf size (Tyree and Jarvis, 1982). As a result, leaves from the three regions showed difference in tissue elasticity that may result from changes in nutrient status, osmotic and pressure potentials, tissue maturity, soil water content, etc. (Correia et al., 1989).

Fig. 3. Trend of soil parameters in relation to sites.

Fig. 4. Trend of stomata parameters in relation to sites.

Fig. 5. Stomata density, and open/closure status of leaves from three visually similar Sidr trees, representing three ecologically different locations namely Khitan, Aqiq, and Makhwah.

Fig. 6. Trend of leaf parameters in relation to sites.

Fig. 7. Leaf size and color from three visually similar Sidr trees, representing three ecologically different locations namely Khitan, Aqiq, and Makhwah.
Aside from the moisture content of the soil, environmental conditions of high light intensity, high temperature, low relative humidity and high wind speed will significantly increase plant water loss. The prior environment of a plant also can influence the development of water stress (Knox and Lehtola, 2005).

**Fig. 8.** Similar branch cuts showing leaf size and color from three visually similar Sidr trees, representing three ecologically different locations namely Khitan (A), Aqiq (B), and Makhwah (C).

The study of soil water parameters, and leaf, and stomata physiological parameters of the Sidr tree reflected the adaptation of the tree to the three different ecological conditions of Al Khitan, Al Aqiq, and Al Makhwah in Al-Baha region, and accounted for its survival on the sites under study. Important directions for future Sidr ecophysiology research include regional variation in the effects of soil and atmospheric conditions and water availability on demography, biomass partitioning to roots and shoots, stomata reactivity, root to shoot communication, and osmotic potential in relation to growth.

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