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Evaporation Reduction from Open Water Tanks Using Palm-Frond Covers: Effects of Tank Shape and Coverage Pattern

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Abstract

The limited fresh water resources and increasing future demand for water necessitate the importance of optimum use of water; especially in arid/semi-arid regions. The purpose of this study is to examine reducing evaporation losses from open water bodies using palm-frond sheets as cover material. Four open constant-depth water tanks with two different surface areas have been used in the study. The tanks had square and rectangular surface areas. The tanks were covered with two patterns of palm-frond sheets: a) staggered strips-no strips covering half of the surface area (strips-covered), and b) single sheet covering half of the surface area (½-covered). Data of cumulative evaporation depths were recorded daily continuously from the covered tanks, as well as from the uncovered tanks, to assess the relative efficiency of evaporation reduction. The results indicated that the strips-covered pattern outperformed the ½-covered; it reduced the evaporation depth by approximately 20% and 24% for the square and rectangular surface tanks; respectively, when compared to the ½-covered pattern. Moreover, the strips-covered pattern resulted in approximately 76% less evaporation depth compared to the uncovered reference tanks. Additionally, water quality analyses showed that such palm-based cover materials have insignificant effect on the water quality. These results confirmed that evaporation can be reduced and controlled using environment friendly safe techniques.

Keywords: *arid zones, evaporation losses, palm fronds, water conservation*

1. Introduction

Water is one of the most precious natural resources in the world, especially in arid and semi-arid zones such as the Kingdom of Saudi Arabia (KSA). The renewable water resources of KSA are significantly less than its non–renewable water resources, due to its fairly low average annual precipitation ranging from 100 mm to 150 mm. KSA experiences, as well, high evaporation rates with average annual rate ranging between 2500 mm and 3000 mm. This shows the need for water conservation techniques; such as reducing evaporation from impounding reservoirs, and puts greater attention to long-term water use for development and sustainability management (Al-Hassoun *et al.*, 2011; Alam and AlShaikh, 2013).

Considering the importance of optimal utilization of renewable water resources, the Government of KSA has been constructing dams on many wadis to harvest rainwater. However, one of the water management challenges in arid regions is the large amount of water loss from the reservoirs of such dams, due to the extremely high evaporation rates. Evaporation losses from dam reservoirs affect their water storage efficiency. Evaporation from open water bodies such as wetlands and lakes often represents the largest loss in their local hydrological budget, yet its quantification still continues to be a theoretical and practical challenge. Thus, there has been an increased focus on evaporation control techniques that can be applied to water storage, due to severe drought conditions in many parts of the world (Anonymous, 2003). Management of water by reducing the evaporation rates will conserve water that can be used to support the ever-growing domestic, agricultural and industrial demands.

One way of reducing evaporation rates from open water bodies; for example, lakes and dam reservoirs, is to partially cover their exposed surface areas to lessen evaporation losses while not affecting water quality. Cooley (1983) tested the effect of long-term exposure of different floating chemicals and physical cover materials on the evaporation reduction efficiency. He showed that evaporation reduction efficiencies ranged from 36% to about 84% depending on the cover type. Craig *et al.* (2005) and Martinez-Alvarez *et al.* (2006) investigated the effect of installing suspended shade-cloth covers and reported they are

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considered one of the most promising options for reducing evaporation. Alvarez *et al.* (2006) examined different types of shading meshes and reported that the shading of pan induced significant decrease of the daily evaporation rate, ranging from 50% for the aluminized screen to near 80% for the colored-polyethylene meshes. Craig *et al.* (2007) observed that the use of physical covers enabled evaporation reduction substantially. They suggested that these types of covers would be more effective for small reservoirs; less than 10 ha in area. Although physical covers can also be used for large reservoirs, they would be uneconomical. One way to reduce the cost and to make it economical is using the local material as the cover. In a more recent relevant study by Xi Yao *et al.* (2010), they employed a 2D-model to estimate evaporation rates on Wivenhoe Dam and tested the effectiveness of suspended and floating covers for evaporation reduction. They concluded that suspended and floating covers have great potential in reducing evaporation through the reduction of energy input. Their results show that if Wivenhoe Dam was fully covered, the annual efficiency of evaporation reduction would reach 76% for suspended covers and 68% for floating covers.

Not only the cover material, but also the number of layers of the cover influences the evaporation rates. Barnes (1993) found that monolayer is potentially most effective in conditions where the rate of evaporation is high. The study by Ikweiri *et al.* (2008) on the Omar Muktar Reservoir tested the effect of the monolayer technique to reduce evaporation in comparison to the cost of the local lost water by evaporation. More recently, Alam and AlShaikh (2013) studied the layer effects of palm-frond sheets that were used to cover standard evaporation pans. They observed that the average reduction in evaporation from a single-layer fully-covered pan was about 47%; whereas it reached about 58% in a double-layer fully-covered pan, when compared to the evaporation from an open uncovered reference pan.

Covering water bodies by chemicals or physical covers has its concerns on water quality of the water bodies. Maestre-Valeroa *et al.* (2011) evaluated the effects of suspended shade-cloth cover on the quality of agricultural water stored on farm. They concluded that the installation of the suspended shade-cloth cover induced positive balance between rainfall and evaporation; hence, conserving water and improving water quality by reducing the electrical conductivity of the water by 8.2%. Their study also showed that the lack of turbulence under the cover and the reduction in photosynthesis reduced the concentration of Dissolved Oxygen (DO) from 16 mg L^{-1} to 1.5 mg L^{-1} and turbidity from 40 NTU at installation to less than 1 NTU eventually. Maestre-Valero *et al.* (2013) further reported that the suspended shade-cloth cover limited the water oxygenation produced by the wind dragging effect on the water surface and the photosynthesis processes. They also reported that the Total Dissolved Solids (TDS) did not seem to be affected by the presence of the cover; neither did the cover have any consequences on the chemical water quality parameters. Accordingly, they concluded that applying such cover material would not involve any modification in the fertirrigation practices. Moreover, the cover greatly reduced the concentration of fecal coliforms and E. coli that might have negative effects on health if statutory thresholds are exceeded.

For the particular application of palm-based products in reducing evaporation from open water bodies, experiments performed by Al-Hassoun *et al.* (2009) over a period of five weeks indicated reduction in evaporation using floating palm-leaves cover of approximately 63% for fully covered pool; whereas for half covered identical pool, it was 26%. In a similar study by Al-Hassoun *et al.* (2011), they observed evaporation reduction from the fully covered pool of about 55%, while from the half covered pool, it was 26%; their measurements lasted for eight months. In their second study, water quality analysis showed that fronds have insignificant effect on water quality. This eliminated concerns on the negative environmental impacts of cover materials. Palm tree is considered to be one of the most important commercial crops widely distributed across KSA that is capable of withstanding extremely hot weather conditions of the arid region (Al-Juruf *et al*., 1988). The number of palm trees in the Kingdom is estimated to be over 21 million, yielding about 210,000 tons of fronds (Alam and AlShaikh, 2013). Palm-based products have also proven successful in reducing peak water temperatures during summer and for saving energy during winter when used as natural insulators for overhead storage water tanks (Fouli, 2013; Fouli *et al*., 2014).

In the present study, the use of two different patterns of palm-frond sheets as physical cover for the reduction of evaporation from different-shape and different-area open water tanks is tested. The two patterns are: a) staggered strips-no strips covering half of the surface area (strips-covered), and b) single sheet covering half of the surface area (½-covered). Four constant-depth tanks of square and rectangular surface area were used. In the same time, water quality parameters; namely DO and electrical conductivity, were also quantitatively evaluated and the effect of evaporation on such parameters were assessed. Shaded covers reduce the energy available for evaporation, reduce wind action over the water surface and trap humid air under the cover; all these factors contribute to evaporation reduction.

This work is considered extension to the work previously done by Al-Hassoun *et al.* (2009, 2011) where their storage reservoirs were of fixed shape. In our present study, the effect of tank shape, surface area and coverage pattern are being newly considered. Our findings have also increased the understanding of the correlation between the climatological parameters and evaporation.

2. Materials and Methods

2.1 Experimental Setup

In this study the effect of the tank surface area, its shape and the coverage pattern on evaporation reduction was investigated. Four tanks having vertical sides and constant depth of 0.50 m were used in the study. Two of the tanks had square surface area, whereas the other two had rectangular surface area. Two surface

Table 1. Details of the Experimental Setup

Tank No.	Tank shape and coverage	Surface Area (m^2)	Dimensions ($L \times W \times D$) (in meters)
1	Rectangle (strips-covered)	1	0.67 × 1.50 × 0.50
2	Rectangle ((½-covered)	1	0.67 × 1.50 × 0.50
3	Square (strips-covered)	0.5	0.71 × 0.71 × 0.50
4	Square ((½-covered)	0.5	0.71 × 0.71 × 0.50

Fig. 1. Sample Photos of the Used Rectangular Tanks and the Coverage Patterns: (a) ½-covered, (b) Strips-covered

coverage patterns were considered: a) staggered strips-no strips covering half of the surface area (strips-covered), and b) single sheet covering half of the surface area (½-covered). The material used for coverage was locally available palm-fronds, which are massive agriculture waste and environment-friendly by-product in KSA. The strips had the dimensions 25 cm × 70 cm and were 5 mm thick. Table 1 lists the dimensions and coverage patterns of the tanks. Fig. 1 shows sample photos of the tanks and the palm-fronds coverage pattern.

Initial experiments were performed to assess the relative performance of the two coverage patterns. The results of those initial experiments showed that the strip-covered pattern performed better than the single-sheet ½-covered pattern. As such, further experiments were done using strip-covered tanks against uncovered reference tanks, to assess the absolute efficiency of evaporation reduction using the strip-covered pattern. Additionally, measurements of climatological factors; i.e. air temperature, humidity and wind speed, as well as of water quality parameters; i.e. conductivity and DO, were recorded and analyzed. While it may be ideal to perform lab experiments under controlled conditions for assessing the effect of each climatological factor separately, the current experiments were performed in the field to mimic real world outdoor weather conditions. The Experiments, observation data, were recorded in the field and are not in controlled condition to separate the effect of temperature due to humidity and wind.

2.2 Data Collection and Measuring Devices

Evaporation depth measurements were taken for the first set of experiments assessing the relative performance of the two adopted coverage patterns during 21 days from 20 March 2013 to 11 April 2013. For the second set of experiments assessing the absolute efficiency of evaporation reduction with respect to a reference uncovered tank, the measurements were taken during 41 days from 7 November 2013 to 14 December 2013. Evaporation depths were obtained by measuring changes in water levels in the tanks; this was done manually using point gauges. The data were recorded at 9:30 AM and 2:00 PM (local time).

The amount of evaporation is a function of air temperature, humidity, wind speed and other ambient conditions. In order to relate evaporation to these parameters, continuous measurements of such parameters were obtained from a nearby weather station at the days of measuring the water levels in the tanks. Water temperatures were also recorded using digital thermometer. Fresh water was added into the tanks to substitute for the evaporated water when the water level dropped to minimum of 20 cm. Conductivity measurements were obtained using Jenway portable conductivity meter with an accuracy 1% of reading and DO measurements were obtained using Jenway Protable dissolved oxygen meter with an accuracy of ± 0.2 mg/L in DO.

3. Results and Discussion

Figure 2 shows the evaporation depths in centimeters against time in hours from the four tanks listed previously in Table 1. The results indicate that the strips-covered pattern reduced the evaporation depth by approximately 20% and 24% for the square and rectangular surface tanks; respectively, when compared to the ½-covered pattern. These percentages are fairly close; it may be therefore indicative that the surface area and tank shape are of marginal effect on the evaporation reduction. The results clearly indicate that the strips-covered pattern outperforms the ½-covered.

As shown also in Fig. 2, from time t = 200 to 360 hours the evaporation depth slightly decreased because of rainfall that happened during that period. In addition to reducing the cumulative evaporation depth, rainfall is usually associated with reduction in the ambient air temperature and hence reduces evaporation.

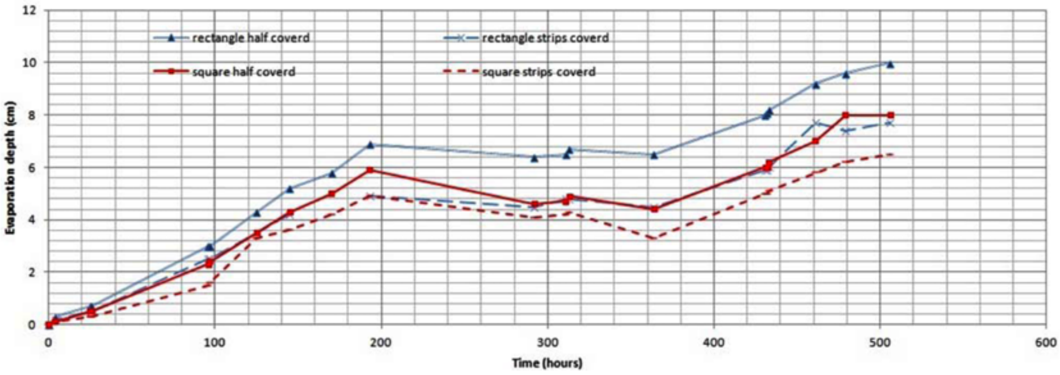


Fig. 2. Evaporation Depth Measurements from the Rectangular and Square Tanks with Time using Different Coverage Patterns

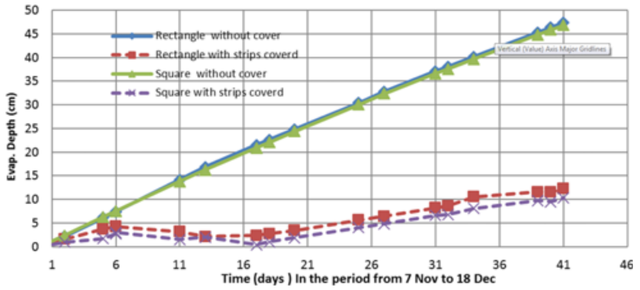
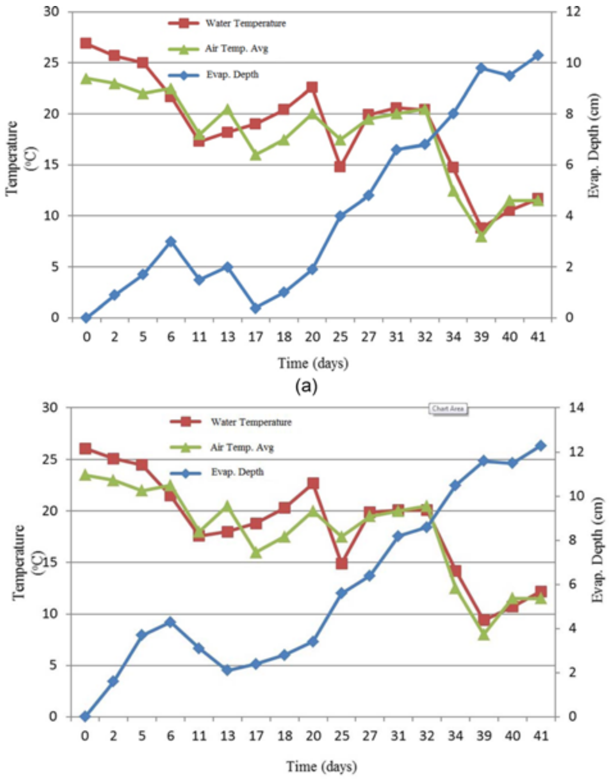


Fig. 3. Comparison of evaporation depths in the strips-covered rectangular and square tanks against uncovered reference tanks

Based on the results in Fig. 2, further experiments were performed assessing the absolute efficiency of evaporation reduction against reference uncovered tanks. Fig. 3 shows the measurements of evaporation depths during 41 days of fall 2013 (from Nov. 7 to Dec. 14). From Fig. 3, it is seen that the overall evaporation reduction in the strips-covered tanks were about 60% and 66% less for the rectangular and square tanks respectively, when compared with the corresponding uncovered reference tanks. These results also indicate that the surface area and shape of the tank have marginal effects on the evaporation depth.

To assess the effect of the different climatological factors on the evaporation depth, the average of measurements of the minimum and maximum daily ambient air temperature, humidity and wind speed were obtained from a nearby weather station at the days the evaporation depths were measured. Fig. 4(a) and Fig. 4(b) show the variation of evaporation depth with average daily ambient air temperature for the square tanks and the rectangular tank, respectively for the case of strips-covered.

The results show that overall as the ambient air temperature increased, the evaporation depth increased, too. It is known that warmer temperatures cause the water molecules to have higher amounts of kinetic energy resulting in larger frequency and magnitude of collisions between water molecules. This would lead consequently to faster rate of evaporation. However, the rate of evaporation not only depends on both the heat available to the liquid and the strength of the intermolecular forces between its molecules; it also depends on the ambient air humidity. Evaporation may be faster on hot sunny days not just because of the extra heat, but also because sunny days are often drier and so have lower relative humidity. On the other hand, if the ambient air is already full of water vapor, it will not have any potential to hold excess vapor and therefore, evaporation will be at much slow rate (Condie and Webster, 1997). It may be noted here that Mahmudul Hassan *et al.* (2015) investigated the effect of geographical and climatological variation on the efficiency of evaporation mitigation using modules of floating materials. They found that evaporation was reduced by 43% and 37% at a coastal site and an arid zone site, respectively. They referred such



(a)

(b)

Fig. 4. Variation of Evaporation Depth with Average Daily Ambient Air Temperature: (a) for the Strips-covered Square Tank, (b) for the Strips-Covered Rectangular Tank

difference to the decrease in radiation contribution to evaporation, condensation bias when calculating the mean daily evaporation rate.

As seen in Fig. 4, the water temperatures were fairly close to the ambient air temperatures; this may be due to the fact that the tanks were metallic, whereas the shown air temperatures are averages of the minimum and maximum daily values. It is to be noted that rainfall occurred on the days 11, 39 and 40. For that reason there was a decrease in evaporation depth on day 11, which is referred to the increase in humidity due the rainfall that concurred. Also, it is shown that there is decrease in the evaporation depth on days 39 and 40, due to the rainfall that occurred during those days as shown in Figs. 4(a) and 4(b) for the two different patterns. The 1.5 cm decrease in evaporation depth that occurred during the days from 11 to 17 corresponds to decrease of almost 4^{o} degrees that happened in the air temperature. This zone, however, shows no correlation between the water and air temperatures such discrepancy might due to the effect of different contact area of the bottom of the tanks with the roof.

Figure 5 shows the variation of evaporation depth in the strips-covered tanks with the average of the minimum and maximum recorded humidity on the days of measuring the evaporation depths. A clear decline in the evaporation depth in the rectangular tank from approximately 4 cm on day 6 to 2 cm on day 13 is obvious due to the increase in humidity from 30% to 85% during the same period. As stated previously, rainfall was recorded on the days 11, 39 and 40.

Figure 6 shows the variation of evaporation depth with the average daily wind speed. The wind speed shows a wavy pattern. At times of increasing wind speed, it is coupled with decrease of evaporation depth; e.g. from day 5 to day 11, whereas at other times of decreasing wind speed, it was coupled with increase of evaporation depths; e.g. from day 2 to day 5 and from day 25 to day 27. This indicates that probably wind speed had little effect on the evaporation depth; possibly due to the large surface area and fetches of the tanks.

Figure 7 shows the temporal variation of conductivity with evaporation depth. From day 17 to day 41, the conductivity and evaporation depth measurements for both strips-covered rectangular and square tanks show that as the evaporation depth increases, the conductivity increases, too. This is because as water evaporates from the tanks, the ion concentrations increase in the tanks leading to increase in conductivity. This is in line with the results reported by Talling (2009) from studies that were done on several lakes in Africa. Also, Summer and Belaineh (2005) indicated that evaporation and precipitation induced salinity changes explained 61% of the variability in conductivity at a flow-restricted part of lagoons. The data from day 1 to day 17 in (Fig. 7) show fluctuating pattern of the evaporation depth that is relatively smaller (within 4 cm) than the continuously increasing trend after day 17. During this first period, the conductivity was almost constant.

Figure 8 shows the variation of DO with evaporation depth. The measurements of DO in both the square and rectangular tanks show no correlation between DO and evaporation depth. This agrees with the results of Al-Hassoun *et al.* (2011) where they reported insignificant effect of the palm-frond sheets on water quality.

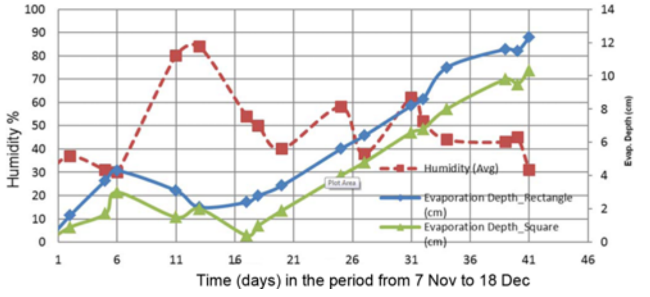


Fig. 5. Variation of Evaporation Depth in the Strips-covered Tanks with the Average Daily Humidity

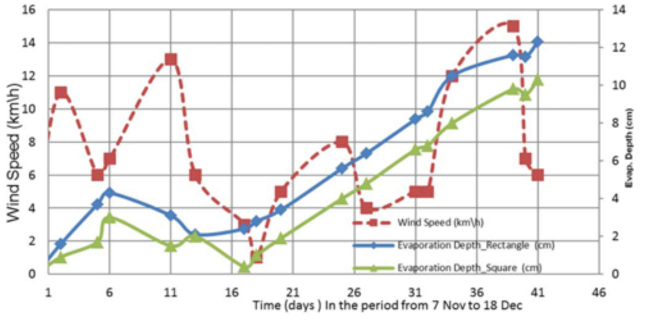


Fig. 6. Variation of Evaporation Depth in the Strips-covered Tanks with the Average Daily Wind Speed

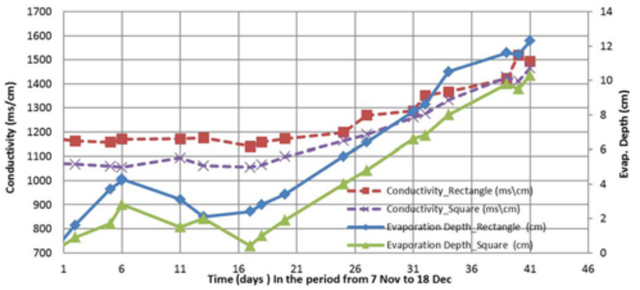


Fig. 7. Conductivity and Evaporation Depth Measurements for the Strips-covered Rectangular and Square Tanks

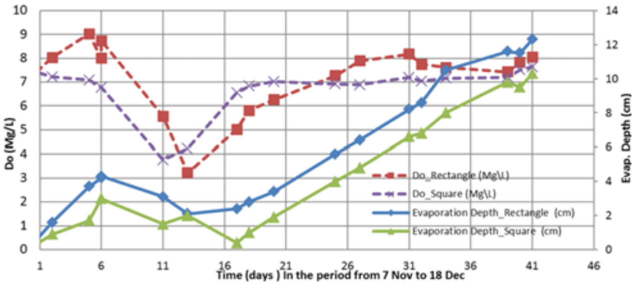


Fig. 8. DO and Evaporation Depth Measurements for the Strips-covered Rectangular and Square Tanks

Comparing our results to those obtained by Al-Hassoun *et al.* (2009, 2011), it can be stated that our strips-covered pattern performed better than their fully-covered or half-covered patterns. While Al-Hassoun *et al.* (2011) reported evaporation reduction efficiency of about 63% for fully-covered pool and 26% for half-covered identical pool; our strips-covered pattern resulted in about 76%. In our study and theirs single layers of 5 cm – thick palm-frond sheets were used. Alam and AlShaikh (2013) observed the average reduction in evaporation from a single-layer fully-covered pan to be about 47%; whereas it reached about 58% in double-layer fully-covered pan, when compared to the evaporation from an open reference pan. However, they used 1.9 mm-thick palm-frond sheets. It may also be stated herein that the strips-coverage allow for better aeration for the aquatic life in the water body; in addition to being of uniform distribution than the half-covered pattern.

4. Conclusions

In the present study, the use of palm-frond sheets as physical covers for the reduction of evaporation from open water tanks having different shapes and surface coverage patterns was tested. Tanks with two surface shapes were used: rectangular and square; both having constant depth, but with different surface areas. Two coverage patterns were examined: a) staggered strips-no strips covering half of the surface area (strips-covered), and b) single sheet covering half of the surface area (½-covered). The effects of different climatological factors; namely: air temperature, wind speed and humidity on the evaporation depth were assessed and quantitative water quality measurements were also analyzed.

1. The results indicate that the strips-covered pattern outperforms the ½-covered pattern. During a period of 21 days, the strips-covered pattern reduced the evaporation depth by approximately 20% and 24% for the square and rectangular surface tanks; respectively, when compared to the ½-covered pattern. The results also indicate the surface area and tank shape are of marginal effect on the evaporation reduction.
2. Comparison between the evaporation depths measured in the strips-covered tanks against those in identical uncovered reference tanks show that the strips-coverage pattern result in approximately 76% less evaporation depth compared to the uncovered tanks.
3. Comparing our results to those obtained by Al-Hassoun et al. (2009, 2011), it can be stated that our strips-covered pattern performed better than their fully-covered or half-covered patterns.
4. Measurements of the climatological factors indicate that the evaporation depth is mainly affected by temperature and humidity. The effect of wind speed seemed insignificant possibly due to the small surface areas of the used tanks.
5. Water quality test results show that the covers have insignificant effect on the water quality. The water quality test results show that conductivity increases as the evaporation depth increases, and that dissolved oxygen does not change significantly with evaporation.
6. Palm tree is considered to be one of the most important commercial crops and is widely distributed across KSA. Palm fronds and leaves are considered as disposed waste after pruning. Therefore, using palm fronds as covers for open water surfaces to reduce evaporation is a good use of disposed waste. Palm fronds are environment friendly material capable of withstanding extremely hot weather conditions of the arid regions and have great potential in reducing evaporation through the reduction of energy input. However, the biological impact of palm fronds on the aquatic ecosystem in large reservoirs is still unknown. Thus, further long-term studies on large water bodies are recommended. Also, it is recommended to develop a 3D evaporation model for more accurate assessment of evaporation-reducing techniques.

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