Optimum Design Parameters of Solar Still Unit Operating toward Olive Mill Wastewater Management

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ABSTRACT

The present study was conducted at a pilot-scale level to investigate the applicability of solar distillation technique for *in situ* management practice at olive mills, by evaluating the system performance regarding condensate productivity on a long-term basis, starting from the beginning of November till the end of July. A model developed based on mass balance approach was used to determine the optimum design parameters required for plant demonstration. Various condensate production rates were obtained for each month with a lower value (0.4 L/m^2.day) obtained during January and a higher value (1.8 L/m^2.day) obtained during July. At a typical olive mill generating 15 m^3/day of olive mill wastewater (OMW) and operating for 75 days, the minimum design depth and area required for plant demonstration were 30 cm and 3250 m^2, respectively.

KEYWORDS: Olive mill wastewater, Solar still unit, Condensate productivity, Design parameters.

INTRODUCTION

Disposal of olive mill wastewater (OMW) represents a significant environmental problem, especially in Mediterranean areas, where it is produced in vast quantities in a short period (Mili, 2004; Niaounakis and Halvadakis, 2006; Hachicha et al., 2009). Implementing an efficient, cheap and environmentally acceptable method for OMW disposal is a challenging obstacle facing local authorities in olive oil-producing countries. In Jordan, unmanaged OMW generated in huge quantities from olive mills poses serious environmental problems (Gharaibeh and Jaradat, 2017). Currently, there are more than 140 three-phase olive mills spread throughout Jordan discharging yearly more than 250,000 m^3 of OMW (Ministry of Agriculture, 2014).

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Several studies have been carried out to address safe disposal or reasonable treatment of OMW. In these studies, various approaches have been adopted, including anaerobic digestion (Borja et al., 1995; Ubay and Ozturk, 1997; Sampaio et al., 2011; Gonçalves et al., 2012), chemical and biological means (Flouri et al., 1996), evaporation ponds (Gharaibeh et al., 2008; Kavvadias et al., 2010; Jarboui et al., 2010) and land spreading (Saadi et al., 2007). However, the practical application of these methods is improper and restricted due to their high cost. Besides, the small size of the production units and their widespread over a large area together with their seasonal operation create difficulty in establishing a centralized treatment plant and disposal facility. Therefore, seeking a decentralized wastewater treatment facility that treats OMW at the source without requiring the construction of long and expensive pipeline networks is important.

With the focus on the treatment of wastewater and the increased use of renewable energy in all sectors, solar stills are good candidates for non-conventional wastewater treatment (E1-Kady and E1-Shibini, 2001). A solar still is defined as a green energy process that uses the free natural energy of the sun to purify contaminated water in order to produce clean water (Asadi et al., 2013). To-date application of solar stills for OMW treatment has been studied only by few researchers. Photocatalysis using solar energy has been proposed by several researchers as a promising method of OMW treatment (Gernjak et al., 2004; Amat et al., 1999; Herrera et al., 1998). They found that such method could be successfully applied to remove the chemical oxygen demand (COD) and other chemical compounds. Potoeglou et al. (2003) studied the performance of the solar still system for distillate productivity and COD removal from OMW at laboratory-scale level and realized that the system could be employed for the same purpose at large-scale level with an optimum water depth of 2 cm. The application of solar distillation for phenols' recovery from OMW has been studied for the first time by Sklavos et al. (2015).

All previous works on solar still performance for OMW treatment were conducted in a short period (1-3 weeks) and at small depths (1-5 cm) without taking into account the seasonal variation in prevailing air conditions. Water depth inside the basin and prevailing air conditions (such as air temperature and sunshine intensity) are critical parameters affecting the production efficiency of solar stills. The decrease in water depth increases the solar still temperature, consequently increasing the evaporation rate and so the productivity of solar still (Nafey et al., 2000; Al-Hinai et al., 2002; Tripathi and Tiwari, 2005; Tiwari and Tiwari, 2006; Kalidasa and Srithar, 2011; El-Sehaii et al., 2015).

The recommended basin water depth in the solar still is in the shallow range of nearly 2-5 cm (Al-Hinai et al., 2002). However, adopting such shallow depths in building an efficient *in situ* solar still unit at the olive mill facility often requires a large area (either for the construction of the distillate unit or as a separate storage), hence increasing cost and rendering the method impractical due to land scarcity around the olive mill facility. Therefore, investigating the solar still efficiency at higher depths on a long-term basis is imperative for process optimization.

In this work, a solar still experiment was conducted at a pilot-scale level for eight months at a depth of 25 cm. Data from previous similar works carried out at two different depths (5 and 14 cm) was used for process optimization. The current article investigates the application of solar distillation technique for *in situ* management practice at olive mills. The optimum design parameters required for plant demonstration are modeled based on the mass balance approach.

MATERIALS AND METHODS

Experimental Work

Samples of raw OMW discharged from a 3-phase extraction system were collected from Al-Shulah olive mill located in Irbid province north of Jordan (Figure 1). The solar still unit with a basin area of 0.47 m^2 was constructed and filled up with OMW up to a depth of 25 cm (equivalent to117 L by volume) (Figure 2). Details of solar still construction and its dimensions are presented elsewhere (Jaradat et al., 2017). This solar still was placed outdoors at Irbid Weather Station (Figure 1), faced south to catch maximum solar radiation and operated for eight months starting from the beginning of November 2015. This location was chosen to benefit from the recorded weather forecasting data measured during the time of the experiment, particularly ambient air temperatures and sun shine hours. The starting date of this experiment was chosen because the olive oil production season in Jordan is usually starting at this time each year. So, if any solar still unit would be constructed and operated at an olive mill, it should be available from the beginning of November to catch the whole OMW generated from the mill.

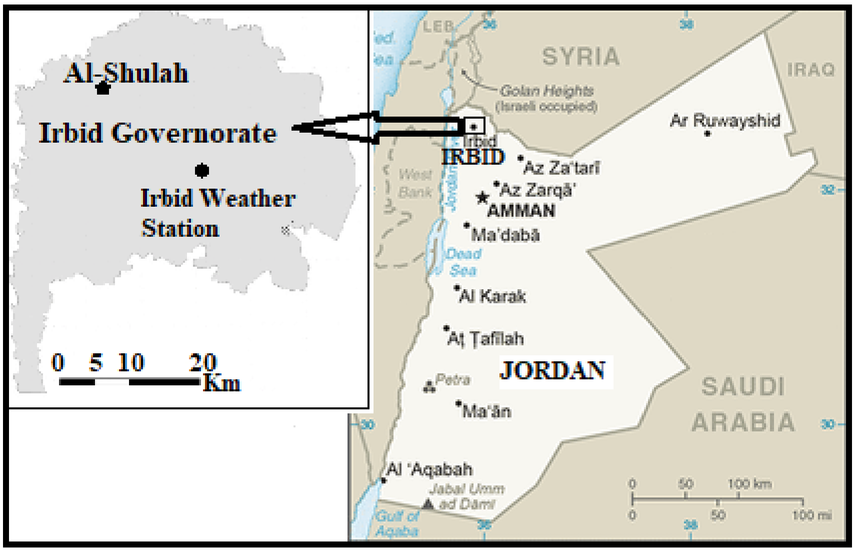

Figure (1): Location of Al-Shulah olive mill and Irbid weather station

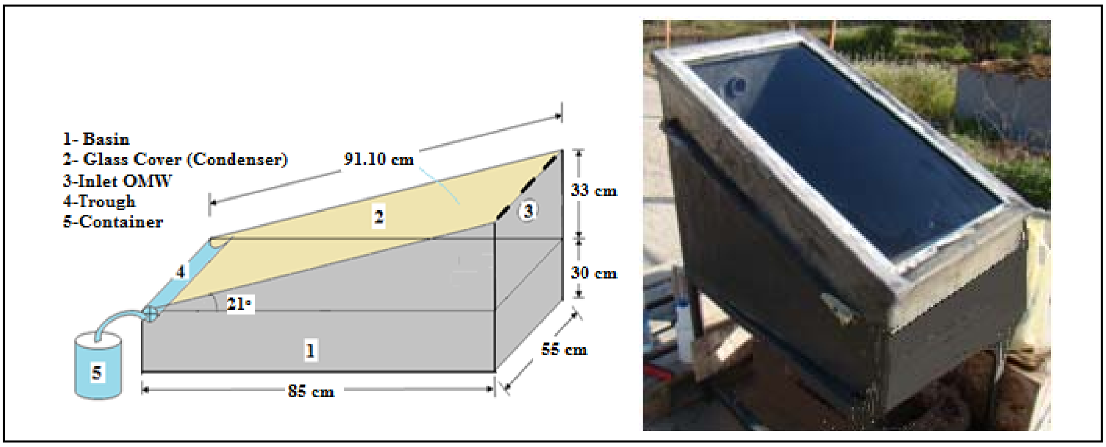

Figure (2): Schematic drawing and actual solar still unit

Inside the solar still, a cm-scale was installed to measure depth reduction and two thermometers were installed to measure air and OMW temperatures during the elapsed time of the experiment. These measurements were recorded daily. Data from similar experiments conducted previously (from November 2014 till July 2015) using similar solar still units and at the same location at two different depths of 14 cm (Jaradat et al., 2017) and 5 cm (unpublished work) was used here for process optimization.

Governing Equations

A model (Figure 3) describing the solar still as a treatment unit at a typical olive mill generatin of 15 m^3/day of OMW and operating for 75 days is proposed based on the mass balance approach (Eq. 1). The typical operational period of olive mills in Jordan starts from the beginning of November till the mid of January every year.

$$\frac{\partial V}{\partial t} = Q_{in} - Q_{out} \tag{1}$$

where V is the volume of OMW [m^3], Q is the OMW volumetric flow or productivity [m^3/day]. The subscripts (in) and (out) stand for the solar still inlet and outlet, respectively. For each time step t [day], the volume of OMW which remained in the solar still V_t is given as:

$$V_t = V_0 + (Q_{in} - Q_{out})\, t \qquad (2)$$

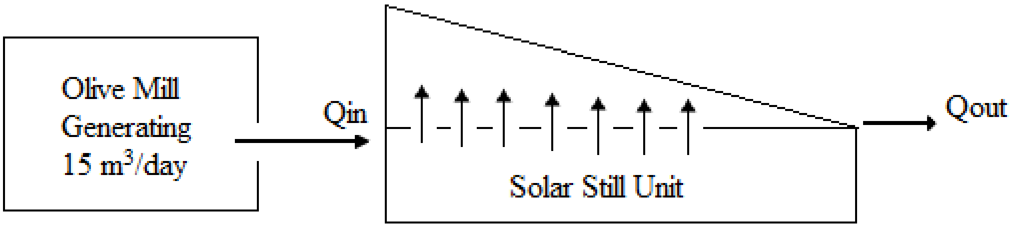

Figure (3): Scheme showing the proposed solar still unit operated at olive mill site

Herein, V_0 is the volume of OMW at t=t_0. Q_{in} = 15 m^3/day for the first 75 days (operational period of olive mills) and Q_{in}=0.0 after 75 days. Q_{out} is calculated as:

$$Q_{out} = \frac{r\,A}{1000} \qquad (3)$$

where A is the solar still basin area [m^2] and r is the OMW distillate production rate [L/m^2 day]. The cumulative OMW production rate P_{cum} [m^3/day] over the whole study period (time step numbers range between i= 1 to N) is then calculated as:

$$P_{\text{cum}} = \sum_{i=1}^{N}\left(Q_{\text{out}}^{i}\right) \qquad (4)$$

In the current work, r is experimentally obtained as a function of OMW depth (h) inside the solar still at different time steps. Linear regression analysis, in the form of ($r = mh+b$), is used for this purpose. The slope m and the intercept b are averaged for each month period. At each time step (1 day herein), h is calculated as:

$$h = \frac{V}{A} \qquad (5)$$

At $t = t_0$, V_0=15 m^3 and hence $h_0 = V_0/A$.

The optimal design parameters of the solar still system were then determined based on several determinantal factors. First, the storage capacity of the solar still unit should be sufficient to receive all OMW coming out from the olive mill. Here, the depth of OMW inside the basin should always be less than the design depth of the basin. Second, the productivity within a reasonable time should approach the total amount of OMW available for evaporation/condensation. In this regard, the total amount of OMW available for condensation is equal to 1013 m^3 (calculated by multiplying the daily discharge (15 m^3/day) by the operational period of olive mills (75 days) by the liquid fraction of OMW). The liquid fraction of OMW equals 90%, because the solid fraction of OMW that remained in the basin at the end of the experiment is approximately 10%. Third, the reasonable time of solar still operation was assumed ≤ nine months. Hence, the process will end up before August leaving three months for solid fraction removal and preparation of the unit for the next olive oil production season. The fourth factor is the minimum area required to achieve full productivity within reasonable time.

RESULTS AND DISCUSSION

A solar still experiment has been conducted starting from 1 November 2015 and continued up to 30 June 2016 until all available OMW in the basin has been evaporated and collected as a condensate.

The depth of the OMW inside the solar still sank significantly from 25 cm (equivalent to 117 L by volume) at the beginning of the experiment to 2.3 cm (equivalent to 10.8 L by volume) toward the end of the experiment, leaving only a solid residual that represents nearly 10% of the total OMW amount. Based on the mass balance approach, the calculated total condensate produced during the elapsed time of the experiment based on depth reduction is 109.5 L. This value agreed well with the total amount of distilled water collected on a daily basis (109.2 L), assuring negligible water loss from the solar still.

Figure 4 shows the variation of OMW temperature inside the basin and the total amount of condensate produced as a function of time. As indicated from Figure 4, the distillate production, initially, experienced a decrease (November toward the end of January) and a progressive increase (during early February to June). The pattern of condensate production agreed with the OMW and the ambient air temperature fluctuation, hence suggesting better performance of the system during the hot season at which high temperatures and long sunshine hours are abundant. The scarcity of the stored OMW available for evaporation/condensation toward the end of June caused a significant drop in the condensate production rate (Figure 4).

The fluctuation of the distillate production rate is also shown in Figure 4. During November, for instance, the distillate production declined at a rate of 0.75 [L/m^2.day]. The recorded distillate production at this month depleted linearly from 0.56 [L/day] to 0.14 [L/day] with an average value of 0.35 [L/day]. In contrast, the distillate production rate increased to reach ~1.8 [L/m^2.day] during June. For the whole study period (i.e., November-June), Table 1 tabulates the distillate production rate for different OMW depths (namely, 25, 14 and 5 cm). The results of 14- and 5- cm experiments were obtained from previous work to serve as a benchmark for comparison with the 25-cm results from the current work.

Figure 5 shows the linear variation (for each month) of the distillate production rate *r* with OMW depth *h*. The formulae which resulted from linear regression analysis are also given (Figure 5). The linear formulae were used in the model to calculate the optimum design area and the optimum design depth required for plant demonstration in order to achieve the best productivity within a reasonable time.

Figure 6 shows the change of the cumulative distillate production and the OMW depth with time for different design areas and design depths. For example, the solar still designed with a depth of 5 cm and an area of 2,000 m^2 (Figure 6A) had not achieved the maximum set cumulative production value (1,013 m^3) within a reasonable time (i.e., 270 days). Moreover, at an area of 2,000 m^2, the OMW depth exceeded the 5-cm designed value. Such findings suggest the unworkability of these design area and depth values. To overcome this problem (i.e., to attain the maximum set cumulative production value of ~1,013 m^3 in a practical time), Figure 6B recommends a minimum design area of nearly 11,000 m^2 for a design depth of 5 cm. This finding disagreed with the work of Potoglou et al. (2003) who recommended a total design area of ~5,250 m^2 (at a design depth of 2 cm) for a typical olive mill facility (operating at ~15 m^3/day). At this area (11000 m^2), the whole OMW available for condensation (1013 m^3) can be produced within 135 days. Furthermore, the depth of OMW had not reached the design depth (i.e., 5 cm). In other words, the storage capacity was enough to handle all OMW coming out from the olive mill during the whole season. However, adopting such a high design area of 11,000 m^2 often increases cost.

To find the optimal design area and depth values of the solar still unit, different values of design areas and depths were tested following the just discussed principle in Figure 6. The summarized findings in Table 2 suggest a decrease in the production time and an increase in the design area as the design depth dropped. Such trend incurred a high cost due to the increase of the necessary design area. The inverse was true with the increase of the design depth. As discussed in prior, the reasonable time of solar still operation was assumed ≤ nine months. Assigning such a time (i.e., nine months which is equivalent to 270 days) as the maximum production time gave a design depth of ~30 cm with a minimum design area of ~3,250 m^2 (Figure 7).

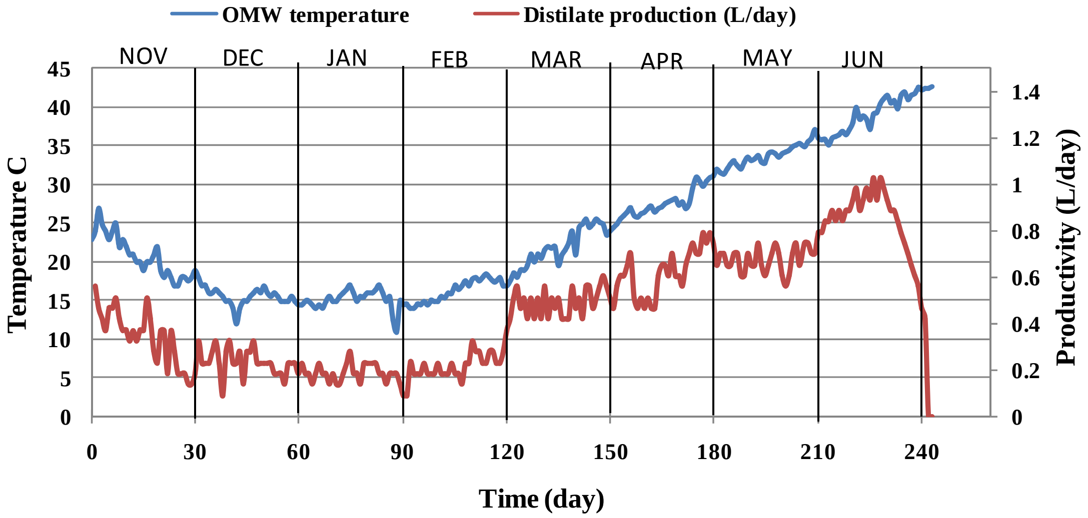

Figure (4): Relationship between OMW temperatures inside the solar still and condensate productivity from November 2015 to June 2016

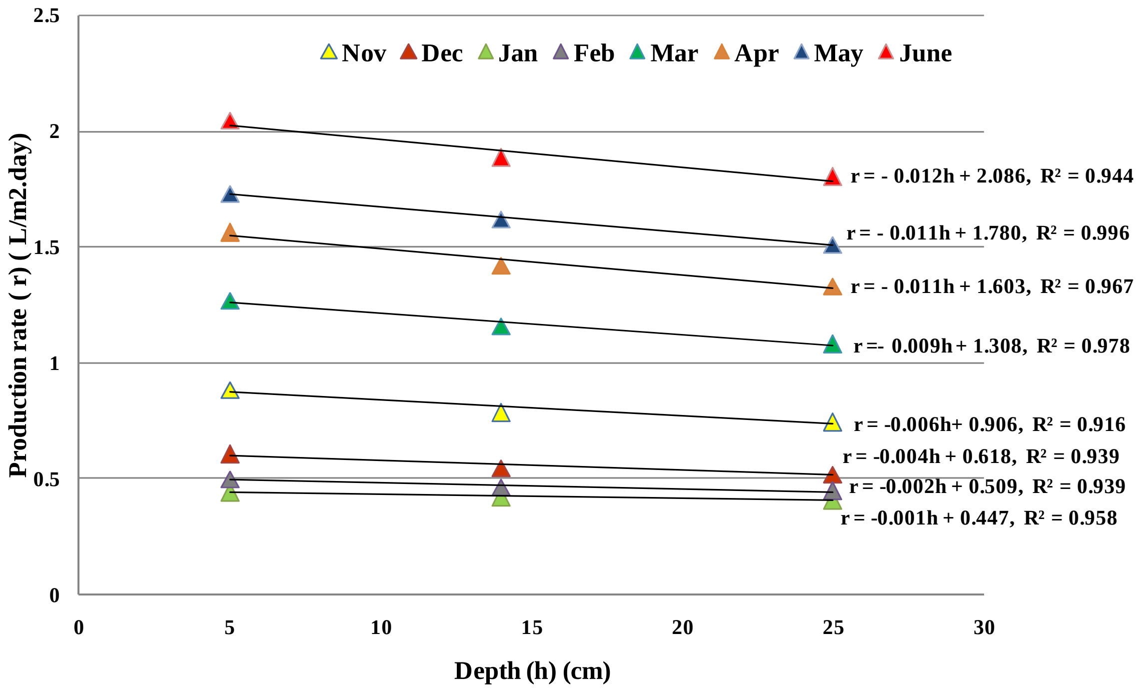

Figure (5): Correlation between OMW depth in the basin (h) and production rate (r)

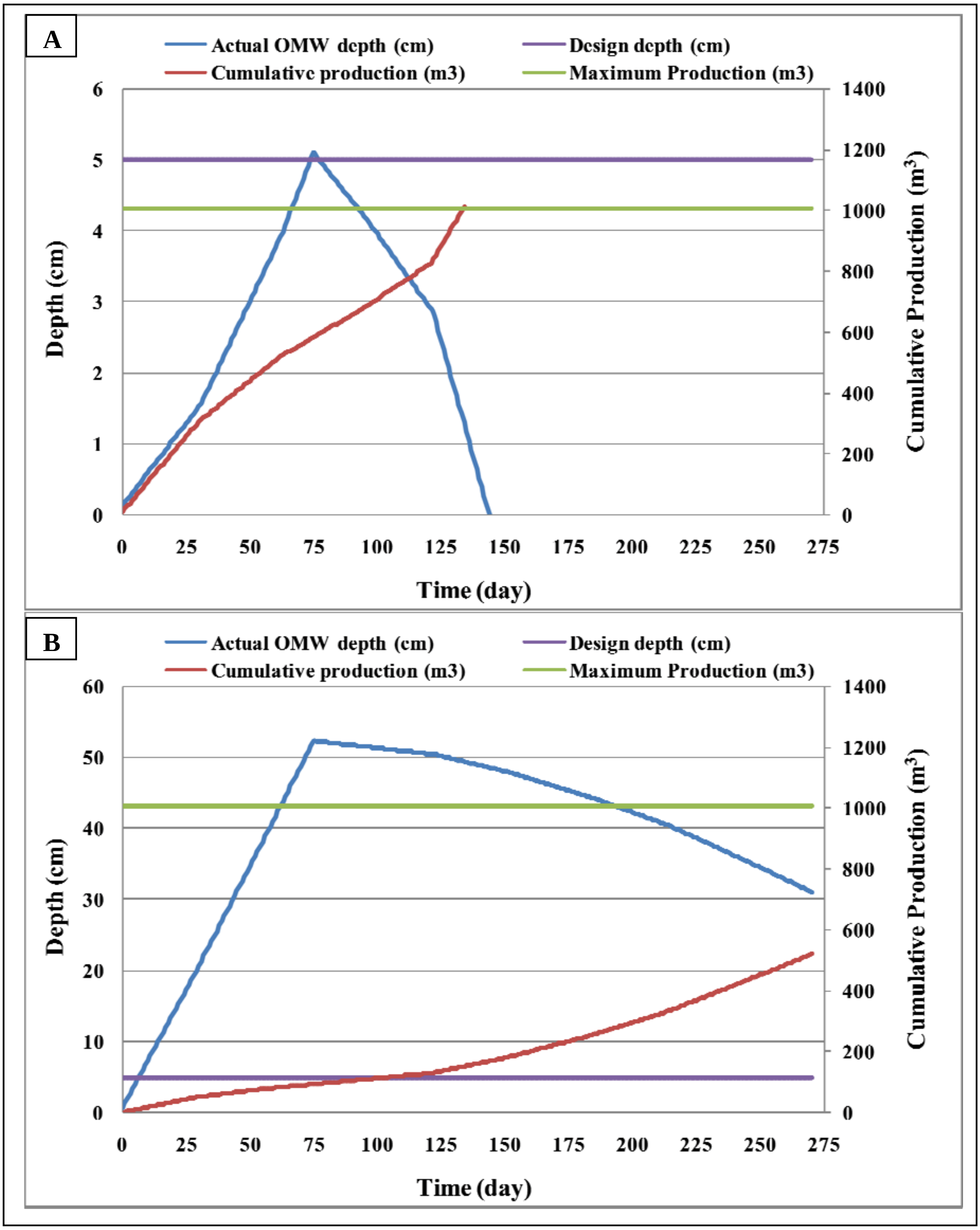

Figure (6): Variation in actual OMW depth and cumulative production of condensed water at (A) a design depth of 5 cm and a design area of 2000 m^2 (B) a design depth of 5 cm and a design area of 11000 m^2

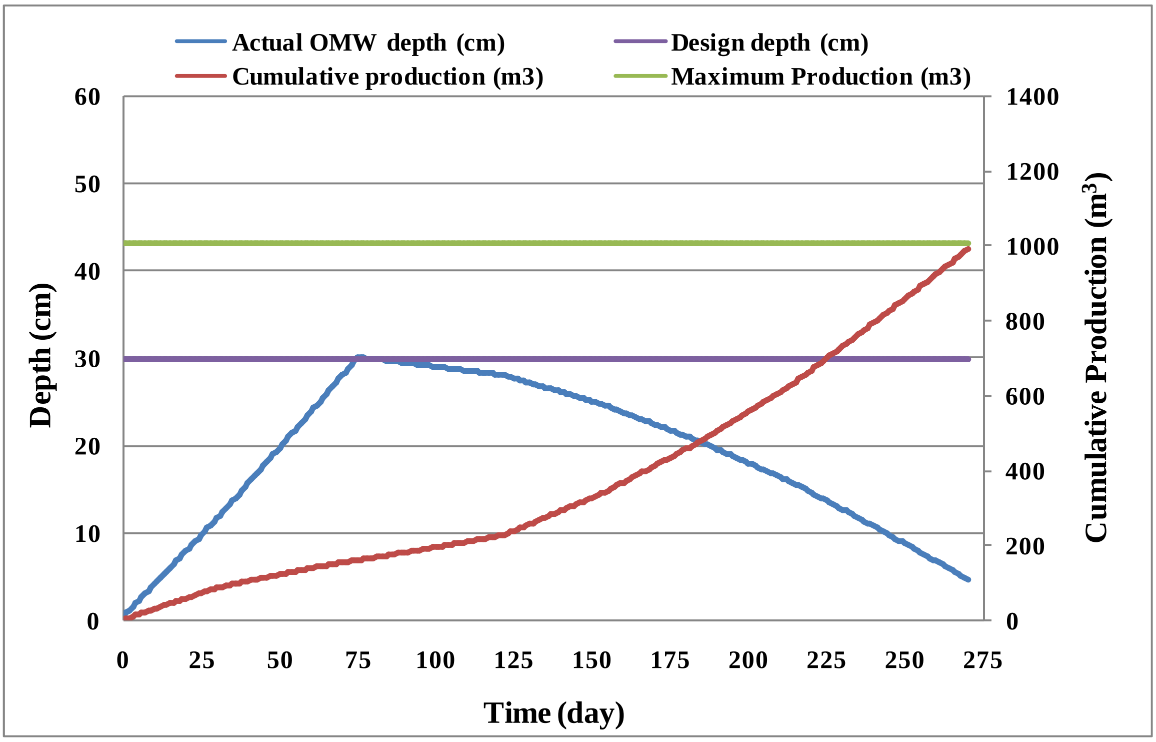

Figure (7): Variation in actual OMW depth and cumulative production of condensed water at a design depth of 30 cm and a design area of 3250 m^2

Table 1. The monthly average values of distillate production rate at different depths (5, 14 and 25 cm)

		Depth (cm)	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June
Production rate (L/m^2.day)	Current work 2015/2016	25	0.745	0.52	0.406	0.446	1.08	1.33	1.51	1.8
	Previous work 2014/2015	5	0.885	0.604	0.441	0.5	1.27	1.56	1.73	2.04
		14	0.786	0.548	0.419	0.464	1.16	1.42	1.62	1.94

Table 2. Time required to produce all available condensed water at different design depths and design areas

Design depth (cm)	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**
Design area (m^2)	11000	7500	5650	4500	3750	3250	2850	2525	2275	2075
Production time (days)	134	164	190	216	237	257	278	299	320	341

The efficiency of such solar still units for organic load removal from OMW has been evaluated in a separate research article (Jaradat et al., 2017). The results obtained revealed that the solar still system can reduce the organic load in OMW significantly, which agreed well with similar works from literature (Potoglou et al., 2003; Sklavos et al., 2015). Moreover, the remaining solid residue had been evaluated in a previous work and proved its utility as a potential biofuel (Gharaibeh and Jaradat, 2017).

These findings suggest the applicability and cost effectiveness to apply the solar still unit on a large scale as a treatment method in olive mill facilities in Jordan and elsewhere in the Mediterranean region.

CONCLUSIONS

The applicability of solar distillation technique for *in situ* management practice of OMW was evaluated *via* experimental work and modeling approach. The system performance was experimentally evaluated regarding condensate productivity on a long-term basis starting from the beginning of November till the end of July. A model developed based on the mass balance approach was used to determine the optimum design parameters required for plant demonstration. Various condensate production rates were obtained for each month with a lower value (0.4 L/m^2.day) during January and a higher value (1.8 L/m^2.day) during July. The optimum design parameters for plant demonstration at the typical olive mill generating 15 m^3/day of OMW were 30 cm (design depth) and 3250 m^2 (design area). Such a simple low-cost technique can be employed on a large scale as a treatment method in olive mills in Jordan and elsewhere in the Mediterranean region.

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