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Efficiency of Monolayers in Evaporation Suppression from Water Surface Considering Meteorological Parameters

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Abstract

The evaporation from water reservoirs has become a global issue, due to climate change, limited water resources, and population growth. In this research, three emulsions of octadecanol/Brij-35 (4:1), hexadecanol/Brij-35 (4:1), and a combination of the alcohols with Brij-35, octadecanol/hexadecanol/Brij-35 (2:2:1), were used in water. One-way ANOVA was applied to compare the mean of evaporation in different chemical and physical methods, and factorial ANOVA was used to investigate the main and interactional effects of different meteorological parameters on the rate of evaporation. Results showed that two physical methods of the canopy and shade balls performed better than the chemical methods, with reductions of 60 and 56 percent in evaporation, respectively. Among the chemical methods, the octadecanol/Brij-35 emulsion had a better performance with a 36 percent of reduction in evaporation. One-way ANOVA results showed that among the chemical methods, only the octadecanol/Brij-35 had no significant difference with shade balls with a 99 percent probability level ($P < 0.01$). On the other hand, factorial ANOVA showed that the temperature and relative humidity had the highest effect on evaporation. Octadecanol/Brij-35 monolayer had a lower performance than two physical methods at low temperatures but after increasing temperature, its performance improved. This monolayer had a good performance at low wind speed compared to physical methods; however, with increasing the wind speed, its performance was severely affected. For temperatures of over 37°, the evaporation rate increased more than 50 percent when the wind speed had changed from 3.5 m/s to more than 8.7 m/s.

1 Introduction

The world is under pressure to make optimal use of water resources because of increasing environmental concerns; for example, in Australia, the rate of evaporation is 2 meters per year, and the average rainfall is 500 mm per year (Erick 2007). At such heat, about 95 percent of the rainfall evaporates before it falls to the ground. Studies have shown that more than half of the water accumulated behind dams and small reservoirs is lost due to evaporation (Craig 2005). Reservoir water loss in hot and dry areas can be significant enough to offset the positive effects of water storage behind dams (Zhang et al. 2017). Field measurements show that the rate of evaporation from Texas reservoirs in the United States is about 7.53 billion cubic meters per year, equivalent to 61 percent of agricultural need or 126 percent of the total drinking water need of the state in 2010. Evaporation rate from reservoirs will intensify during periods of recent drought (Wurbs and Ayala 2014). Another study on Texas reservoirs shows that about 20 percent of the useful volume of reservoirs is wasted annually due to evaporation. According to this study, in five coastal basins, reservoir evaporation losses were higher than the minimum freshwater flow required to maintain sustainable ecosystem health (Zhang et al. 2017). A study on 721 dam reservoirs in the United States showed that the amount of water lost from these reservoirs was more than 30 billion cubic meters per year, equivalent to 93 percent of the annual public water supply in the United States (Gao et al. 2008). The increase in evaporation rate from dam reservoirs due to climate change, and the increase in reservoir water level due to sediment deposition were other worrying points in this regard (Gao et al. 2008). Due to evaporation, 17.88 million cubic meters of water was lost from Qaraoun Dam in Lebanon during 2013. If this amount of water was used for the electricity generation, it would be worth 850,000 $, which only contained 5.1 percent of the loss. On the other side, the impact of evaporation on irrigation has been more significant, and the damages of evaporation in this sector are estimated about 43 million dollars (Bou-Fakhreddine et al. 2019).

Today, various tools have been used to deal with surface evaporation, such as shade cover structures, covering the water's surface with thin layers of polyethylene, shade balls, and large canopies. Implementing these structures is not practical in large dimensions, and costs much money, and is only suitable for small scales. Biological coatings, such as lilies and mosses, have a potential to reduce evaporation from the water surface. These coatings have not received much attention due to their very low efficiency (Cooley and Myers 1973). The blue lentil plant can be used as an environmentally friendly cover to reduce evaporation from the water surface. The results obtained from this aquatic plant show that the vegetation of blue lentils has reduced the evaporation till about 9 percent. In addition, aeration increases the growth of water lentils and further reduces evaporation (Soltani et al. 1399). Fixed hexagonal coating is widely used in South Africa. The light color of these coatings reduces heat absorption. This coating is fire resistant and has a lifespan of 15 years, and its lifespan will increase if it is protected and maintained (Watts, 2005). Constructing the plant windbreaks decreases evaporation from the water surface by reducing the wind speed (Elshafei et al. 2021). Shade physical coatings evaluated by the Australian National Centre for Engineering in Agriculture can be used in reservoirs smaller than 10 hectares or reservoirs behind small dams, but in large reservoirs, it is uneconomical because of high costs (Craig 2005). Investigating the effect of counterweighted spheres on the evaporation rate from agricultural reservoirs in arid regions showed that in the presence of these spheres in the irrigation season evaporation from reservoirs reduced by more than 70 percent (Han et al. 2020).

Monolayer is a thin layer with a molecular thickness of 2 nm that prevents evaporation from the water surface. Most monolayers have been described as compounds of long-chain fatty alcohols such as steel and sterile alcohols that disperse spontaneously in contact with water (La Mer and Healy 1965). Monolayers reduce evaporation by creating a thick layer coating on the water surface (Panjabi et al. 2016). Hexadecanol forms a layer as thick as a molecule on the surface of the water because the molecules of the monolayers have a hydrophilic head from one pole and a hydrophobic tail from the other pole. Therefore, when these molecules are placed in the water, their direction changes so that one pole is in the water and the other is out of the water (Reddy 2005). The low need for monolayers in large surfaces is one of the practical reasons for applying monolayers to reduce evaporation from the water surface; for example, 2 kg of hexadecanol can cover one square Km. The use of monolayers increases the thickness of the boundary layer and the evaporation resistance. Monolayer materials are often easily and rapidly degraded by bacteria, so their efficiency is within a period of 1 to 3 days (Chang et al. 1962). Attempts to reduce evaporation from reservoirs and free water surfaces by using chemical compounds are not novel. Since the 1960s, volatile oils and a thin layer of monolayers have been used as a protective layer against evaporation (Frenkiel 1965). However, in the 1950s, a method was proposed to develop the distribution of monolayers based on cetyl alcohol. A decrease in evaporation rate was observed by spraying these materials on the surface of the reservoir with agricultural use (Mansfield 1955). The low cost of preparation, easy spray on the water surface, and high speed of distribution are the advantages of monolayers. The limitations of their use are their short life and the negative effect of wind on their performance. These thin films could be created by surfactants or some polymers, or a combination of both. The surfactants spread on the surface quickly, and reduces the surface tension of the water. The tendency of these materials located at the boundary of the water and air creates an almost single-molecular thin layer of these materials on the surface of the water. Another idea to improve evaporation retardation is using a combination of two long chain alcohols as monolayer composition. For instance, Ikweiri et al. (2008) on the Omar Mokhtar Dam achieved an evaporation reduction of about 17 percent with using a substance based on a mixture of steel alcohol and stearyl alcohol. Their results showed that 80 to 100 grams of this substance could cover the area of one hectare of water.

Due to technical, operational, economical, and environmental considerations, alcohol-based monolayers could be used widely as an evaporation suppression method. Although pure hexadecanol powder has used in many field trials due to the fast-spreading rate of hexadecanol, the use of octadecanol is very limited because of its low spreading rate. To overcome this obstacle, some new thin films have been created by combination of the known alcohols with a surfactant as emulsifier. As reported in the literature, combination of the octadecanol and hexadecanol with an emulsifier can reduce evaporation from the water surface (Roberts 1962; Desai et al. 1990; O'brien 2006; Barnes 2008). The surfactants facilitate spreading of the heavy alcohols on the water surface, significantly reduced the amount of the material dispersing into the bulk water instead of spreading at the interface. These materials were located at the boundary between water and air creates as a single-molecular thin layer. Due to the nanometer thickness of this layer, the amount of material used with emulsifier is very small in comparison with pure alcohols. Non-ionic surfactant Brij 78, polyoxyethylene (20) stearyl ether, is a common emulsifying agent, already used in the composition of monolayers (Herzig et al. 2011).

In the present study, three emulsions of heavy alcohols with a Brij-35 were used as evaporation suppression monolayers. Two physical methods of the canopy and shade balls were used to evaluate the efficiency of the emulsions. The novelty of this research lies in the application of one-way and factorial analyses of variance (ANOVA) to investigate the effect of the meteorological parameters on the efficiency of evaporation suppression methods. The interaction effect of the meteorological parameters on evaporation from the water surface is also considered in the present study.

2 Material And Methods

2.1 Study Area

This research was conducted near Ahvaz Airport meteorological station with a latitude of 31° 32', longitude of 48° 66', and altitude of 16 m above sea level. In order to conduct the research and evaluate the efficiency of different methods in reducing evaporation from the water surface, Class A evaporation pans with a diameter of 120.7 cm and a depth of 25 cm made up of galvanized iron were used. The experiments were performed during a 35-day period between August 27 and September 30, 2018. Due to the effect of different meteorological parameters on the rate of evaporation from the pans, it was necessary to consider all methods of reducing evaporation on the pans simultaneously. Therefore, six evaporation pans were used near the meteorological station. A wooden base of 15 cm height was placed under all of pans, and the pans were situated on them. The location of the experiments at Ahvaz meteorological station with class A evaporation pans adjacent to the station is shown in Fig. 1.

The evaporation data can be used more confidently if the pans are located at the national standard climate stations or near the reservoir. However, the measured evaporation rate in this case is higher than the evaporation rate of the pans immersed in water (Althoff et al. 2019).

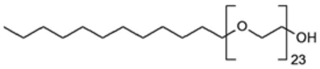
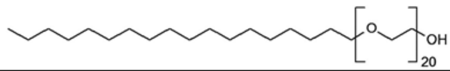
The type of pan, its location, and water quality along with temporally and spatially variations could affect the pan coefficient (Finch and Calver, 2008; Althoff et al. 2019). The rate of evaporation from the pans immersed in water accurately demonstrate reservoir evaporation (Masoner and Stannard, 2010). Therefore, the evaporation rate of the pans placed inside the reservoir is used to determine outside pan coefficient. Lake evaporation could be estimated using the pan coefficient technique, $E_{lake} = K.E_{ClassA}$, where E_{lake} is evaporation from the lake (mm/d), E_{ClassA} is evaporation from standard Class-A evaporation pan located on the land surface, and K is pan coefficient which used to scale pan evaporation to real evaporation (McJannet et al. 2017). The pan coefficient is usually considered between 0.7 to 1.1, according to the conditions of each region. (Varma 1996). However, in many studies, a value of 0.7 is used for the Class-A pans (McJannet et al. 2017). Accordingly, the rate of evaporation from the pan can be used as a reference to compare the performance of evaporation suppression methods.

2.2 Monolayer compounds

Some common volatile emulsifiers used in the composition of monolayers are not economically and ecologically suitable, so Brij-78, which does not have the mentioned problems and is able to form emulsions with heavy alcohols is used in recent studies (Brink et al. 2017). In the present study, three emulsions of heavy alcohols with a Brij-35, polyoxyethylene (23) lauryl ether, emulsifier as octadecanol/Brij-35 (4:1), hexadecanol/Brij-35 (4:1), and a combination of the alcohols with Brij-35, octadecanol/hexadecanol/Brij-35 (2:2:1), were used as monolayers (Fig. 2).

In this work, Brij-35, which melts at lower temperatures compared to Brij 78, making it easier to use, was applied to make the emulsion. On the other hand, presence of three more –(OCH_2CH_2)- groups with a shorter alkyl chain in the structure of Brij-35 compared to the structure of Brij-78, making easier its interaction with water. Table 1 presents the physical properties of Brij-35 and Brij-78.

Table 1. Physical properties of Brij-35 and Brij-78

	Brij-35	Brij-78
Chemical name	Polyoxyethylene (23) lauryl ether	Polyoxyethylene (20) stearyl ether
Molecular formula	$C_{12}H_{25}(C_2H_4O)_{23}OH$	$C_{18}H_{37}(C_2H_4O)_{20}OH$
Density	1.05 g/mL	0.964 g/mL
Flash point	>110 °C	>110 °C
Melting point	39-43 °C	56-60 °C
Boiling point	100 °C	100 °C
Molecular structure		

To prepare the emulsions of alcohol/Brij-35 with 4:1 ratio of the components, a mixture of 4.0 g heavy alcohol (octadecanol or hexadecanol) and 1.0 g Brij-35 was vigorously stirred in 95.0 g of distilled water at 70 ° C for about 30 min. The suspension then was cooled to room temperature slowly. The 2:2:1 emulsion of octadecanol/hexadecanol/Brij-35 was also prepared by a mixture of 2.0 g octadecanol, 2.0 g hexadecanol, and 1.0 g Brij-35 in 95.0 g of water. These emulsions can be used for up to 6 months (Varma 1996; Brink et al. 2017). In the following, the word Brij has been used instead of Brij-35. To prepare hexadecanol emulsion, 4 percent hexadecanol and for hexadecanol + octadecanol emulsion, 2 percent octadecanol with 2 percent hexadecanol were used in the above combination. Accordingly, three types of monolayers were prepared according to the mentioned instructions: hexadecanol emulsion, octadecanol emulsion, and octadecanol + hexadecanol emulsion. In order to evaluate the required concentration of mentioned compounds, the different concentrations of emulsion were prepared. The various injections performed over two days were compared with the control pan, which showed the positive effect of different emulsions on the evaporation reduction for concentrations above 0.2 mL. Therefore, experiments were performed for a concentration of 0.4 mL (11.4 mg/m^2). In this study, in addition to chemical compounds, physical methods such as canopy and shade balls, were used to investigate the monolayers efficiency. Performance of chemical and physical methods were investigated in 5 Class A evaporation pans compared to the control pan. In the shade balls treatment, 100 percent of the pan surface was covered by shade balls with a diameter of 5–6 mm. In the canopy treatment, the distance of the pan from the canopy was about 30 cm. Some studies indicate that using octadecanol and hexadecanol do not significantly affect water properties such as electrical conductivity, temperature, pH, etc. (Piri et al. 2010). Therefore, in this study, only the parameters of water temperature and evaporation rate were measured.

2.3 Analysis of variance

In this study, one-way and factorial ANOVA were used to evaluate the performance of different evaporation suppression methods. At first, a one-way ANOVA was used to investigate the significant differences between evaporation suppression methods, and then a factorial ANOVA was used to investigate the effect of different meteorological parameters on the evaporation methods. All parameters must follow the normal distribution to some extent for using the variance analysis. The quantile-quantile (Q-Q) plot is a graphical technique for determining if two data sets come from populations with a common distribution. The Q-Q plot was used to investigate the normality of data by using normal distribution as the second dataset. The Q-Q plots of all the parameters used are shown in Fig. 3. Closeness of the data and the normal distribution values showed that the normality assumption was correct.

The independent variables must have a nominal or ordinal scale for using ANOVA. Accordingly, all meteorological parameters were divided into three levels: high, medium, and low. Various meteorological parameters, at first, were modified based on the average of each parameter. It means that the average of each parameter was subtracted from all data of that parameter. In such a case, the average data of that parameter will be equal to zero. Then, the data of each parameter was divided into three levels based on the standard deviation (Sd). Values less than − 1Sd were used as low level, values higher than + 1Sd were applied as high level, and values between − 1Sd and + 1Sd were considered as intermediate values. The statistical characteristics of different meteorological parameters during the experiment period are shown in Table 2.

Table 2
Statistical characteristics of various meteorological parameters

	Minimum	Maximum	Mean	Std. Deviation	Level 1	Level 2	Level 3
Temperature (°C)	31.40	39.10	34.74	2.41	< 32.33	32.33–37.15	> 37.15
Relative Humidity	15.50	57.50	35.78	11.64	< 24.14	24.14–47.42	> 47.42
Sunny Hours (hour)	6.80	11.80	10.16	1.22	< 8.94	8.94–11.38	> 11.38
Wind Speed (m/s)	2.00	12.00	6.08	2.63	< 3.45	3.45–8.71	> 8.71

3 Results

3.1 Efficiency of evaporation suppression methods

The results of the average evaporation from the water surface in different physical and chemical methods are presented in Fig. 4. The two physical methods of the canopy and shade balls are more efficient than the chemical methods and have been able to reduce the rate of evaporation to a considerable extent. The average evaporation from the pan in the two physical methods of canopy and shade balls were 3.84 and 4.28 mm, respectively, which compared to the control pan (9.72 mm), these two methods reduced the evaporation from the surface by 60 and 56 percent, respectively. Octadecanol/Brij emulsion, with an average of 6.27 mm and a 36 percent reduction in evaporation, performed better than the other two chemical methods.

The two emulsions of hexadecanol/Brij and hexadecanol/octadecanol/Brij also reduced evaporation by 25 and 21 percent, respectively. This rate of evaporation reduction is similar to the efficiency of commercial materials named water-saver (Sepaskhah 1397). Varma (1996) also showed that heavy alcohols could reduce evaporation from the water surface up to 40 percent, which is consistent with the findings of this study. Naseh and Shahidi (2019) estimated the reduction of evaporation from 50 to 70 percent by shadow balls, which is consistent with the results of this study. Piri et al. (2010) reported a reduction in evaporation using heavy alcohols between 40 and 55 percent. According to the results of these researchers, octadecanol emulsion has a higher efficiency than hexadecanol, which is similar to the results of the present study. Figure 5 shows the water temperature of evaporation pans for all physical and chemical methods. Based on Fig. 5, the water temperature of the pans containing the monolayer is almost the same as the control pan. The water temperature of the pan with canopy is less than the control pan. In the case of using shade balls, the temperature was higher on most days, which is consistent with the results of Afkhami et al. (2019). Preventing the wind from affecting on the water in the pan by covering the water surface, and absorbing more heat from the sun by shade balls and transferring it to the water, make the temperature of the shade balls treatment higher than other pans.

3.2 Comparing the evaporation suppression methods using One-way ANOVA

One-way ANOVA on different evaporation suppression methods showed that the difference between the means was statistically significant. All evaporation reduction methods were compared in pairs, and the differences between the mean evaporation of different methods were statistically investigated by Bonferroni analysis. According to Bonferroni test results (Table 3), evaporation from the control pan significantly differed from all pans at a 99 percent probability level. Evaporation from the canopy pan had a significant difference with all methods used except for shade balls. Shade balls significantly differed from all chemical methods except for octadecanol, which indicated higher efficiency of this monolayer compared to the two other emulsion.

Table 3
Bonferroni test results on the mean evaporation from different treatments

(I) Method	(J) Method	Sig.	Lower Bound	Upper Bound	(I) Method	(J) Method	Sig.	Lower Bound	Upper Bound
Control	Canopy	.000	4.08	7.67	Octadecanol	Control	.000	-5.24	-1.66
	Ball	.000	3.64	7.22		Canopy	.001	.632	4.21
	Octadecanol	.000	1.66	5.24		Ball	.018	-0.18	3.77
	Hexadecanol	.001	0.70	4.28		Hexadecanol	1.000	-2.75	0.83
	Octa. Hexza.	.013	0.24	3.83		Octa. Hexza.	.299	-3.20	0.37
Canopy	Control	.000	-7.67	-4.08	Hexadecanol	Control	.001	-4.28	− .70
	Ball	1.00	-2.23	1.34		Canopy	.000	1.59	5.17
	Octadecanol	.001	-4.21	− .63		Ball	.000	1.14	4.73
	Hexadecanol	.000	-5.17	-1.59		Octadecanol	1.000	-0.83	2.75
	Octa. Hexza.	.000	-5.63	-2.04		Octa. Hexza.	1.000	-2.25	1.33
Ball	Control	.000	-7.2298	-3.64	Octa. Hexza.	Control	.013	-3.83	− .24
	Canopy	1.00	-1.34	2.23		Canopy	.000	2.04	5.65
	Octadecanol	.018	-3.77	0.18		Ball	.000	1.60	5.19
	Hexadecanol	.000	-4.73	-1.14		Octadecanol	.299	-0.37	3.20
	Octa. Hexza.	.000	-5.19	-1.60		Hexadecanol	1.000	-1.33	2.25

According to Table 3, all chemical methods used do not significantly differ from each other. The coefficient of determination in one-way ANOVA was calculated to be 0.4, which showed that the type of evaporation suppression method can estimate about 40 percent of the evaporation. Therefore, the rate of evaporation from the pan, in addition to various evaporation suppression methods, is also affected by other parameters such as meteorological parameters.

3.3 Factorial ANOVA based on the main and interactional effects

Factorial ANOVA was used after converting the independent meteorological parameters from quantitative scale to qualitative mode. The results of this analysis are shown in Table 4. According to Table 4, in addition to the significant effect of evaporation suppression methods, determined by one-way ANOVA, the parameters of temperature, relative humidity, and sunshine duration also had a significant effect on evaporation. The type of evaporation reduction method had the highest effect on the rate of evaporation based on the values of Partial Eta Squared and F parameters. Air temperature and relative humidity had almost the same effect on evaporation. The interaction of different meteorological parameters did not have a statistically significant effect on the rate of evaporation. Based on the factorial ANOVA, the coefficient of determination was calculated to be 0.8, which showed that the proposed model can estimate about 80 percent of the evaporation rate according to the type of evaporation suppression method and meteorological parameters.

Table 4
Factorial ANOVA results based on the main and interactional effects of different parameters on evaporation rate

Source	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	1677.40	29	57.84	24.13	.000	.79
Intercept	1836.19	1	1836.19	766.17	.000	.81
Code	559.19	5	111.83	46.66	.000	.56
Temperature	80.10	2	40.05	16.71	.000	.15
Relative Humidity	67.30	2	33.65	14.04	.000	.13
Sunny Hours	48.50	2	24.25	10.11	.000	.10
Wind Speed	4.66	2	2.33	0.97	.380	.01
Relative H. * Wind S.	0.46	2	0.23	0.09	.908	.00
Relative H. * Sunny H.	1.60	1	1.60	0.66	.415	.00
Temp. * Relative H.	10.47	2	5.23	2.18	.115	.02
Sunny H. * Wind S.	0.12	1	0.12	0.05	.817	.00
Temp. * Wind S.	0.22	1	0.22	0.09	.761	.00
Temp. * Sunny H.	4.28	1	4.28	1.78	.183	.01

3.4 Mean intergroup differences of meteorological parameters

The Bonferroni test was used to investigate the effect of different meteorological parameters on the rate of evaporation (Table 5). According to Table 5, there is a significant difference between the levels of 1 and 3 and the level of 2 and 3 of temperature. There was also a significant difference between all the levels in terms of relative humidity and sunshine duration. Although the speed of wind did not have a significant effect on the rate of evaporation, a significant difference was observed between the levels of 1 and 3 and also the levels of 2 and 3.

Table 5
Bonferroni test results in the mean intergroup differences of meteorological parameters

	(I) Factor	(J) Factor	Mean Difference	Std. Error	Sig.		(I) Factor	(J) Factor	Mean Difference	Std. Error	Sig.
Temperature	1	2	− .22	.29	1.00	Sunny Hours	1	2	-3.31*	.28	.00
		3	-3.66*	.31	.00			3	-7.09*	.35	.00
	2	1	.22	.29	1.00		2	1	3.31*	.28	.00
		3	-3.43*	.22	.00			3	-3.78*	.26	.00
	3	1	3.66*	.31	.00		3	1	7.09*	.35	.00
		2	3.43*	.22	.00			2	3.78*	.26	.00
Relative Humidity	1	2	1.70*	.26	.00	Wind Speed	1	2	− .44	.31	.46
		3	3.05*	.32	.00			3	-1.62*	.39	.00
	2	1	-1.70*	.26	.00		2	1	.44	.31	.46
		3	1.35*	.25	.00			3	-1.18*	.28	.00
	3	1	-3.05*	.32	.00		3	1	1.62*	.39	.00
		2	-1.35*	.25	.00			2	1.18*	.28	.00

Figure 6 shows the effect of different meteorological parameters on the efficiency of physical and chemical evaporation suppression methods. The effect of different temperature levels on the rate of evaporation showed that at a low-temperature level, octadecanol monolayer had a lower efficiency than the two physical methods, but after increasing temperature, its performance increased compared to physical methods. The other two chemical methods had weak performance at a low-temperature level so that no effect of the combination of octadecanol and hexadecanol on evaporation was observed at a low-temperature level. Based on Fig. 6b, at a low relative humidity, the octadecanol emulsion has a lower performance than physical methods, but at the highest level of relative humidity, its performance improved compared to physical methods. Among the two physical methods, similar performance was observed at a low relative humidity, but at a high level of humidity, the canopy performed better. Figure 6c shows that with increasing the sunshine duration, the performance of the two physical methods is becoming close to each other, and the efficiency of the octadecanol is reduced. Comparing the evaporation rate with sunshine duration showed that the rate of evaporation increases from control treatment and chemical methods similarly. Figure 6d shows the effect of the wind speed on the performance of chemical methods. The octadecanol emulsion, at low wind speeds, performed similarly to the physical methods, but as the wind speed increased, its performance was severely affected, and its efficiency decreased. The results obtained in this section were consistent with the observations of Piri et al. (2010). The results of Varma (1996) showed that with increasing the wind speed to about 7 m/s, the efficiency of heavy alcohols was significantly reduced. Gallego-Elvira et al. (2013) also showed that wind of 3 m/s causes the monolayer to disintegrate and reduce its efficiency. For the two physical methods, due to the complete coverage of the water surface by the canopy and shade balls, the evaporation rate changes very small with increasing the wind speed.

3.5 The effect of wind speed on evaporation rate

According to previous researches, one of the effective parameters on the performance of monolayers was wind speed (Varma 1996; Piri et al. 2010; Gallego-Elvira 2013). In this study, the interaction of this parameter and other meteorological parameters pertaining to the performance of the octadecanol monolayer was investigated. In the Factorial ANOVA, at first, only the main effects of meteorological parameters were considered on the evaporation rate from the pan containing octadecanol monolayer (Fig. 7). In the second step, the interactions along with the main effects were added in the analysis of variance (Fig. 8). In Fig. 7, considering only the main effects, the wind speed has a direct effect on the rate of evaporation, so that in all cases, as the wind speed increases, the rate of evaporation also increases. Figure 8, which contains the main effects and the interactional effects of independent parameters, clearly shows the impact of the interactional effects on the rate of evaporation. In Fig. 8a, at high temperatures, the rate of evaporation increases sharply with increasing wind speed. At high temperatures (level 3), the rate of evaporation increased by more than 34 percent by changing the wind speed from level 2 to level 3, and with increasing the wind speed from level 1 to level 3, the evaporation rate will increase by 50 percent. According to Fig. 8b, at a low relative humidity, there is a significant difference between evaporation at various wind speeds. However, with increasing relative humidity, this difference decreases so that at a high relative humidity, the wind speed has a slight effect on the rate of evaporation in the presence of the monolayer. Figure 8c shows that in a high sunshine duration, the effect of wind speed on evaporation rate increases.

4 Conclusion

One of the disadvantages of using pure alcohols as monolayers is their poor spreading on the water surface. In the case of octadecanol, a high amount of powder particles needs to disperse into the bulk water, which contaminates water resources. Using the surfactant emulsifiers such as Brij-35 can significantly improve the spreading rate of the materials with much higher evaporation resistance. Based on experiments and statistical analysis, physical methods show better performance than chemical methods. Comparing the average evaporation in different methods showed that two physical methods of the canopy and shade balls had the best efficiency with a reduction of 60 and 56 percent in evaporation, respectively. Among the chemical methods, the octadecanol/Brij emulsion with a 36 percent reduction in evaporation had a better performance than two other emulsions, and in some cases, had an efficiency close to the physical methods. Although the performance of monolayers is less than physical methods, due to the advantages such as easy to use, less significant damage to the environment, etc. monolayers can be used on a large scale. Meteorological parameters had a very high effect on the rate of evaporation from the water surface; therefore, the effect of these parameters on the performance of monolayers should be investigated. The results of factorial ANOVA showed that the effect size of evaporation reduction methods was 0.56, while temperature and relative humidity had an effect of 0.16 and 0.14 on evaporation, respectively. Investigating the effect of wind speed on the performance of octadecanol at different levels of relative humidity showed that at a high humidity, wind speed had a negligible effect on the monolayer efficiency. In contrast to relative humidity, at high temperatures, wind speed had a significant impact on the rate of evaporation from the water surface in the presence of a monolayer. In order to use the results of this study, it should be considered that the effects of wind speed and relative humidity in large reservoirs are generally higher than over the land surface. According to Fig. 6b, high relative humidity can increase the efficiency in the case of the octadecanol monolayer. However, according to Fig. 6d, increasing the wind speed has reduced the monolayer performance. In order to better analysis of real conditions, the interaction effects of wind speed and relative humidity parameters should be used. According to Fig. 8a, which shows the interaction of relative humidity and wind speed, the efficiency of the octadecanol monolayer has improved with increasing both of relative humidity and wind speed.

Declarations

Ethical Approval and Consent to Participate “Not applicable”

Consent to Publish The authors give their full consent for the publication of this manuscript.

Authors’ Contributions Mehrdad Karimzadeh: manufacturing chemical solutions and performed the experiments, writing early version of the manuscript. Javad Zahiri: interpreting the results, performing ANOVA analysis, writing the final version of the manuscript. Valiollah Nobakht: designing and manufacturing chemical solutions.

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Competing Interests The authors declare that they have no competing interests.

Availability of data and materials All data generated or analyzed during this study are included in this manuscript.

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Figures

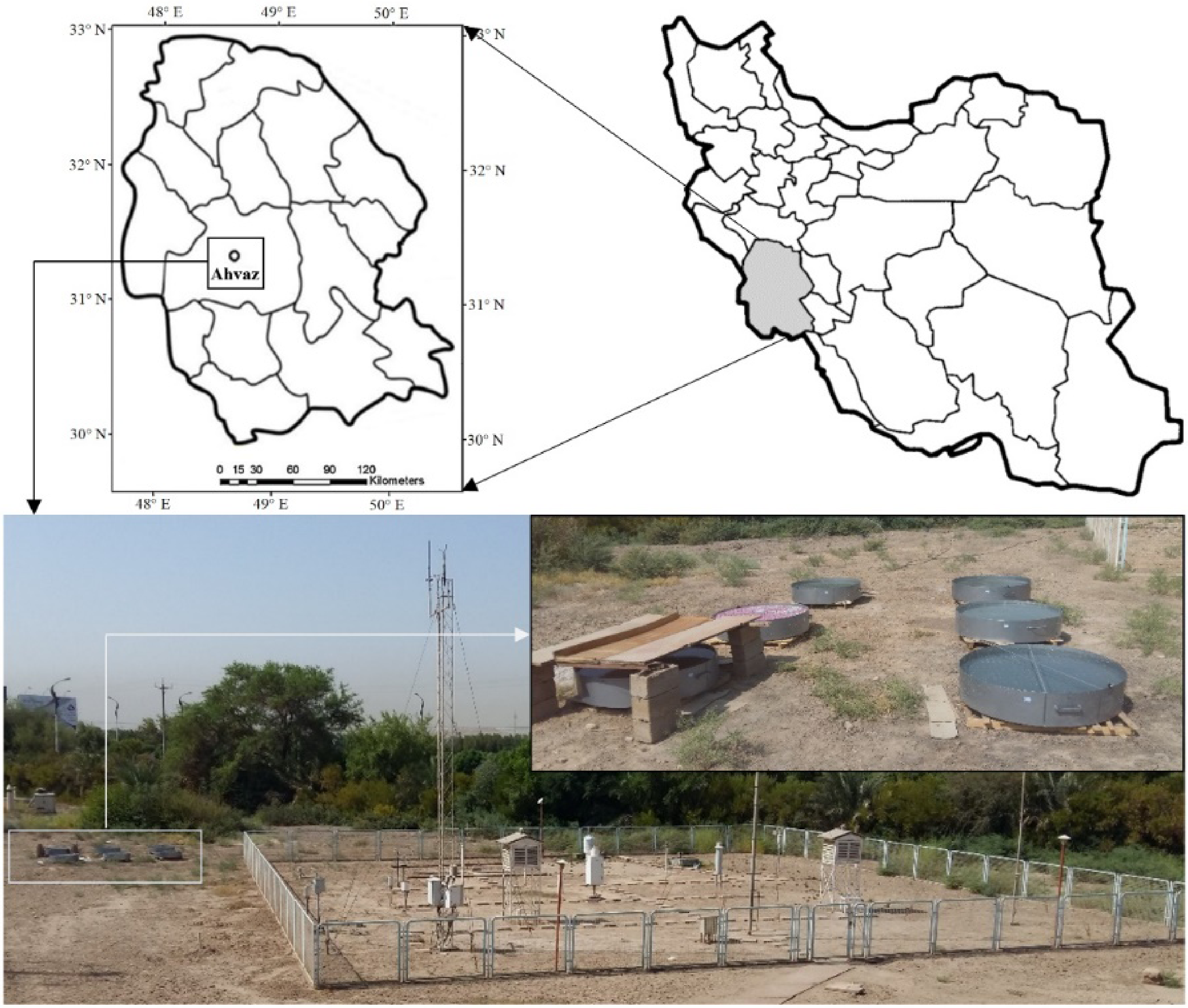

Figure 1

Location of Ahvaz meteorological station with Class A evaporation pans used in the research

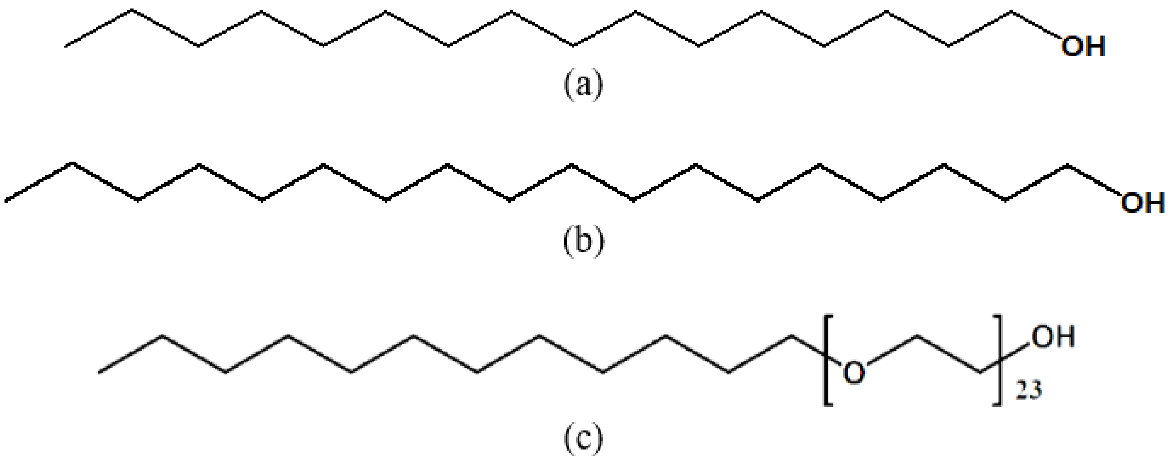

Figure 2

Chemical structure of a) hexadecanol, b) octadecanol, and c) Brij-35

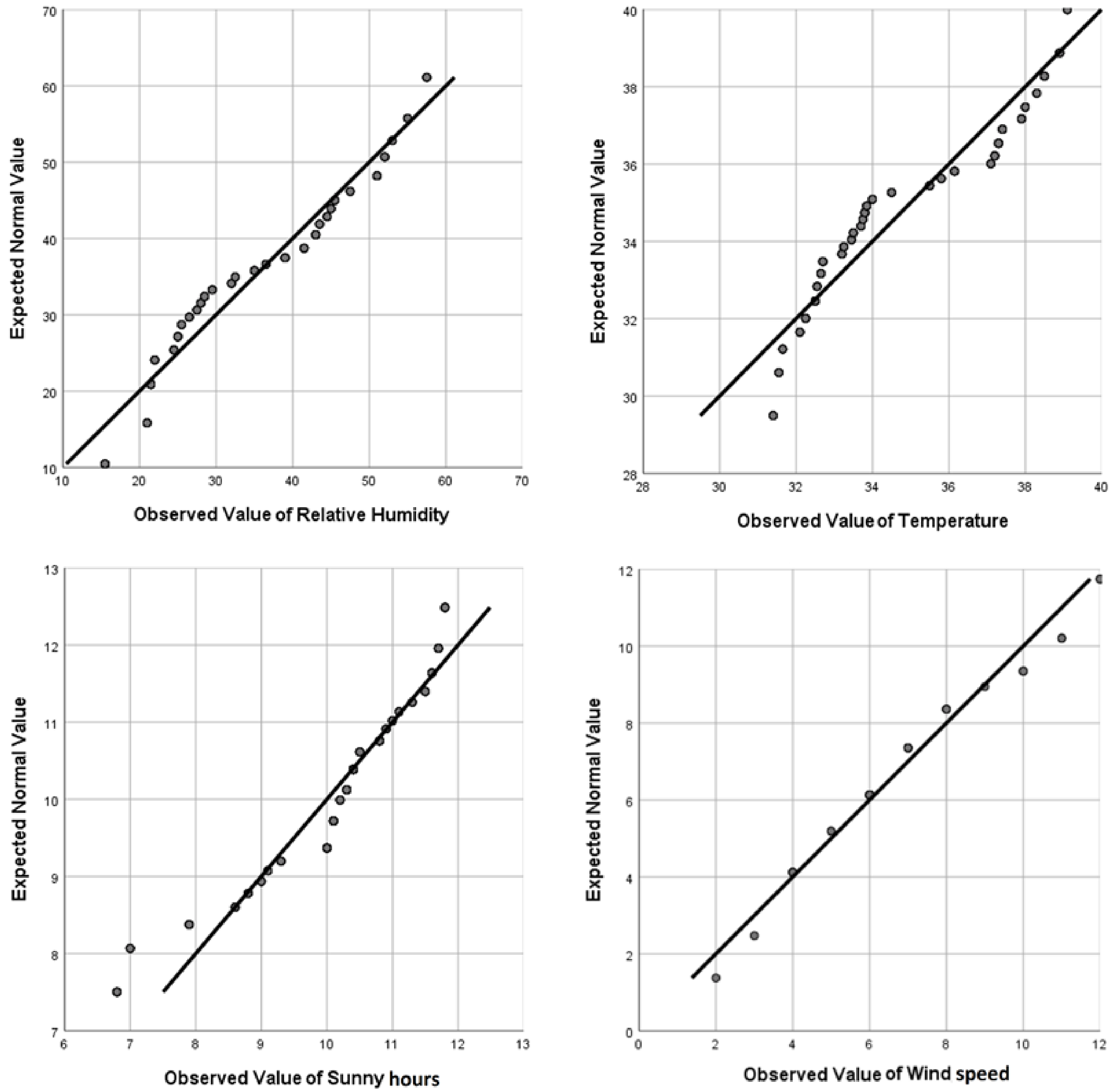

Figure 3

Normality evaluation of data by Q-Q plot

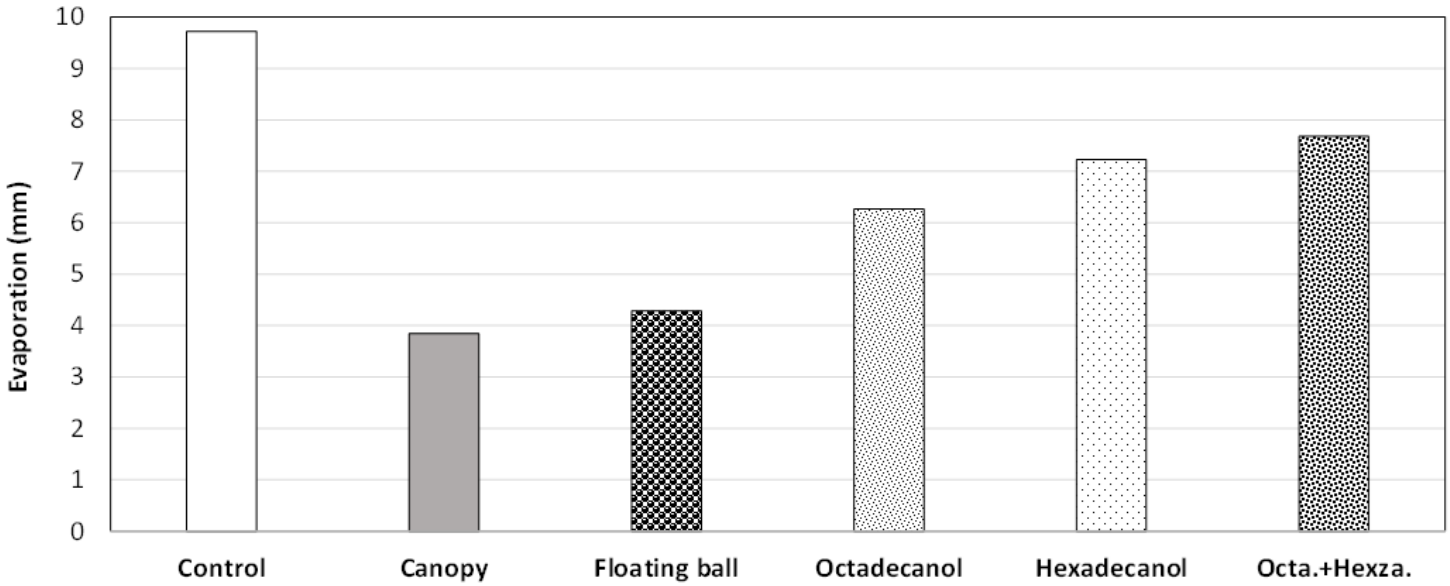

Figure 4

Efficiency of evaporation suppression methods

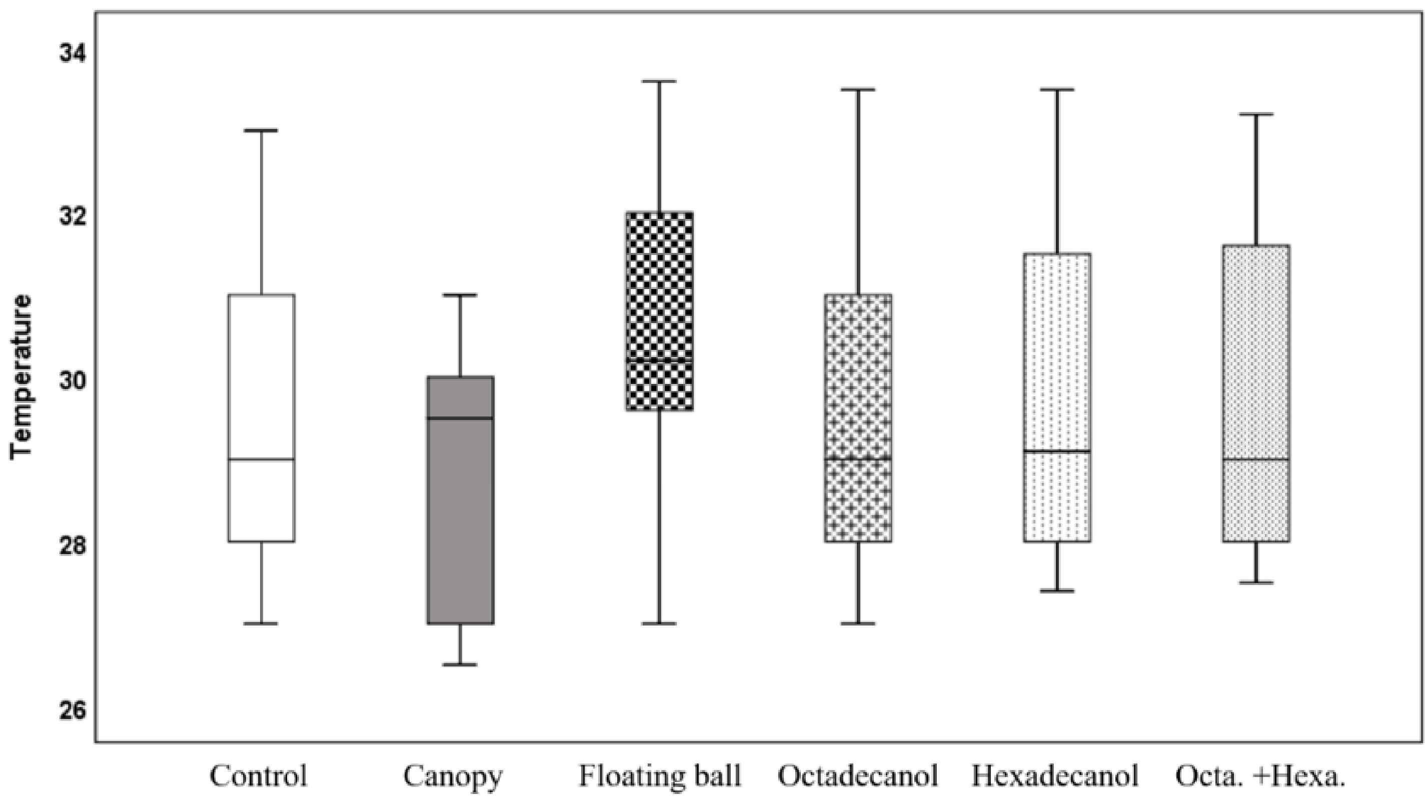

Figure 5

Comparison of evaporation pan temperatures in different treatments

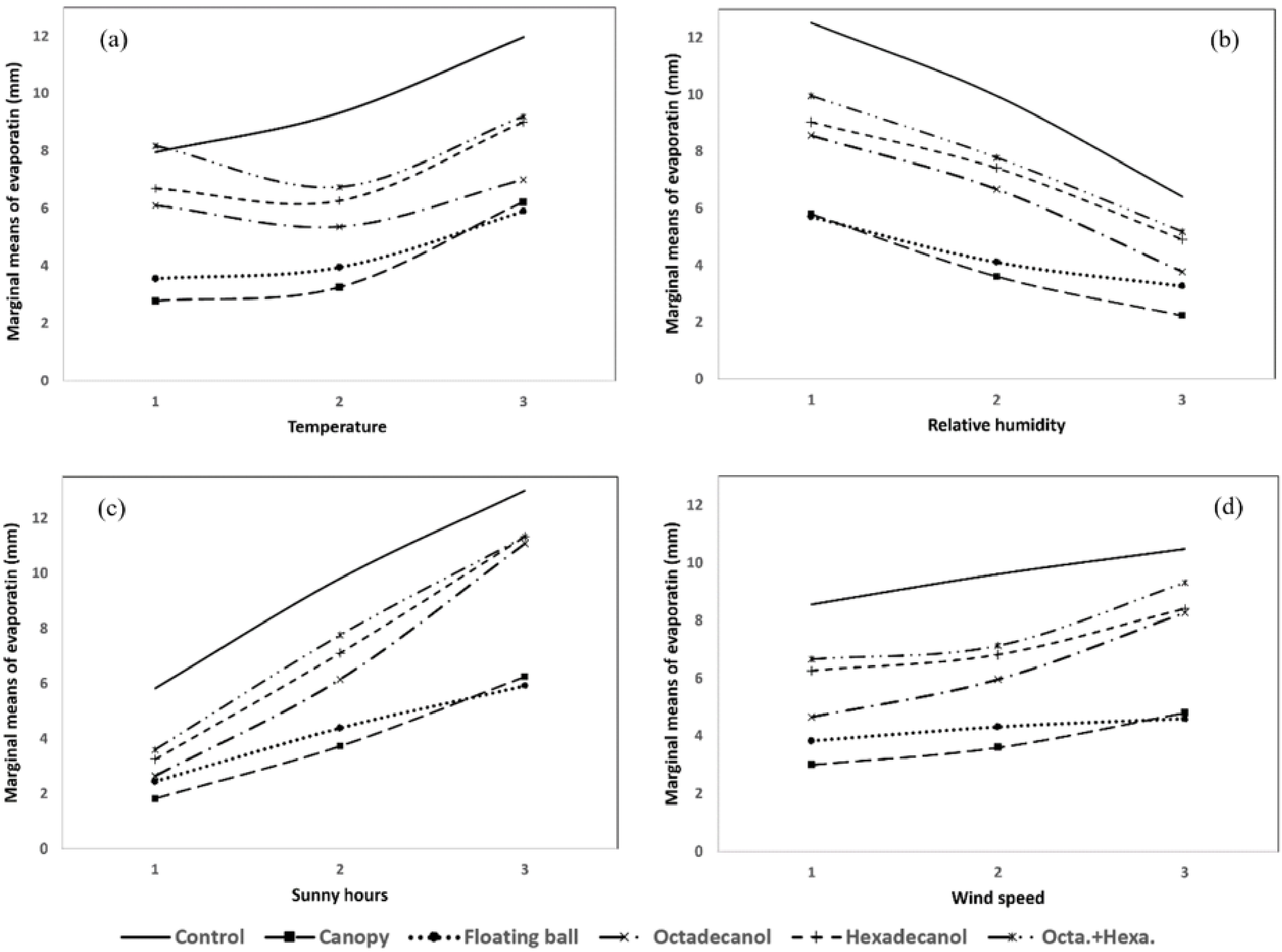

Figure 6

The effect of different levels of the meteorological parameters on the performance of evaporation suppression methods

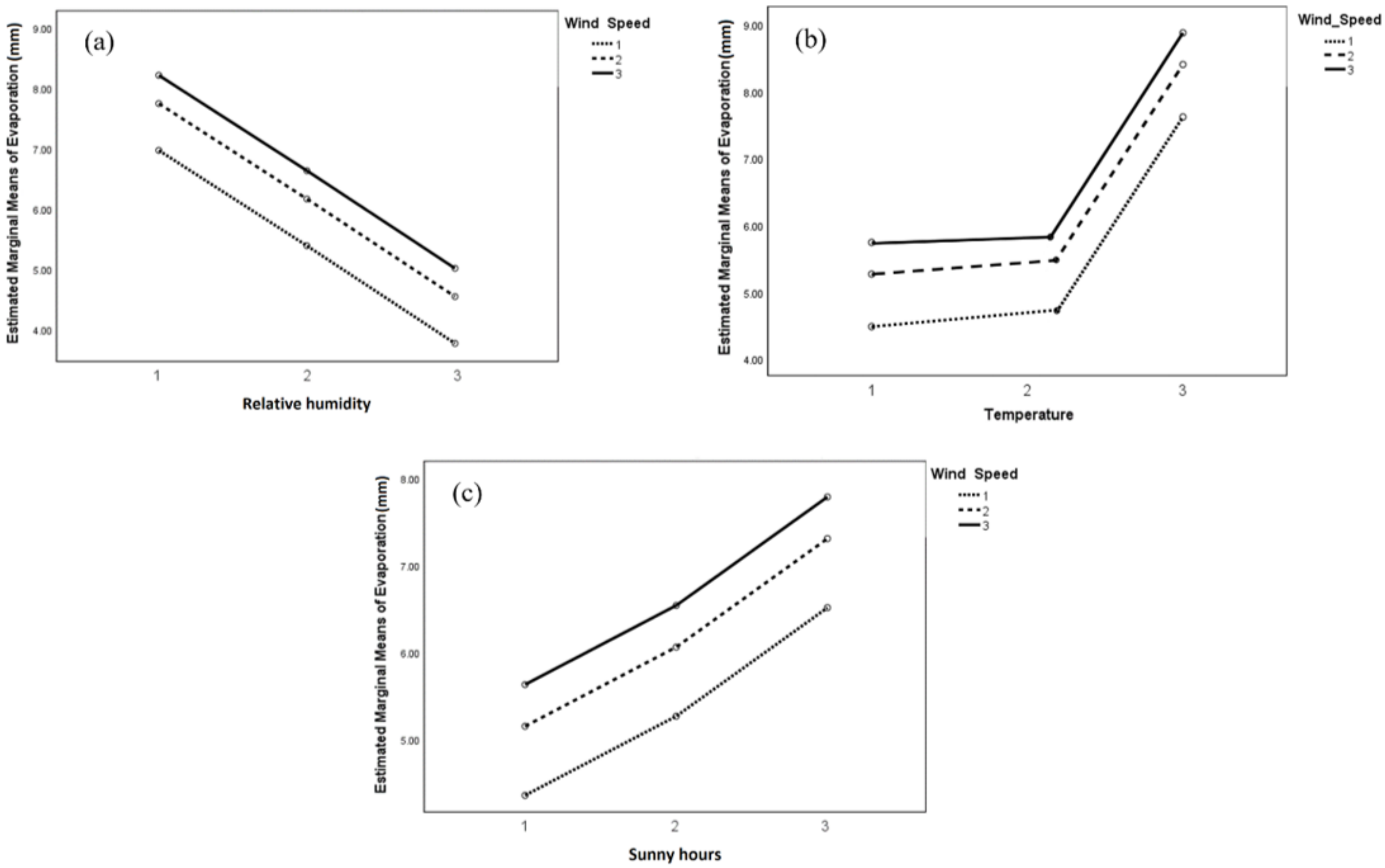

Figure 7

The effect of wind speed on evaporation rate without considering interactional effects

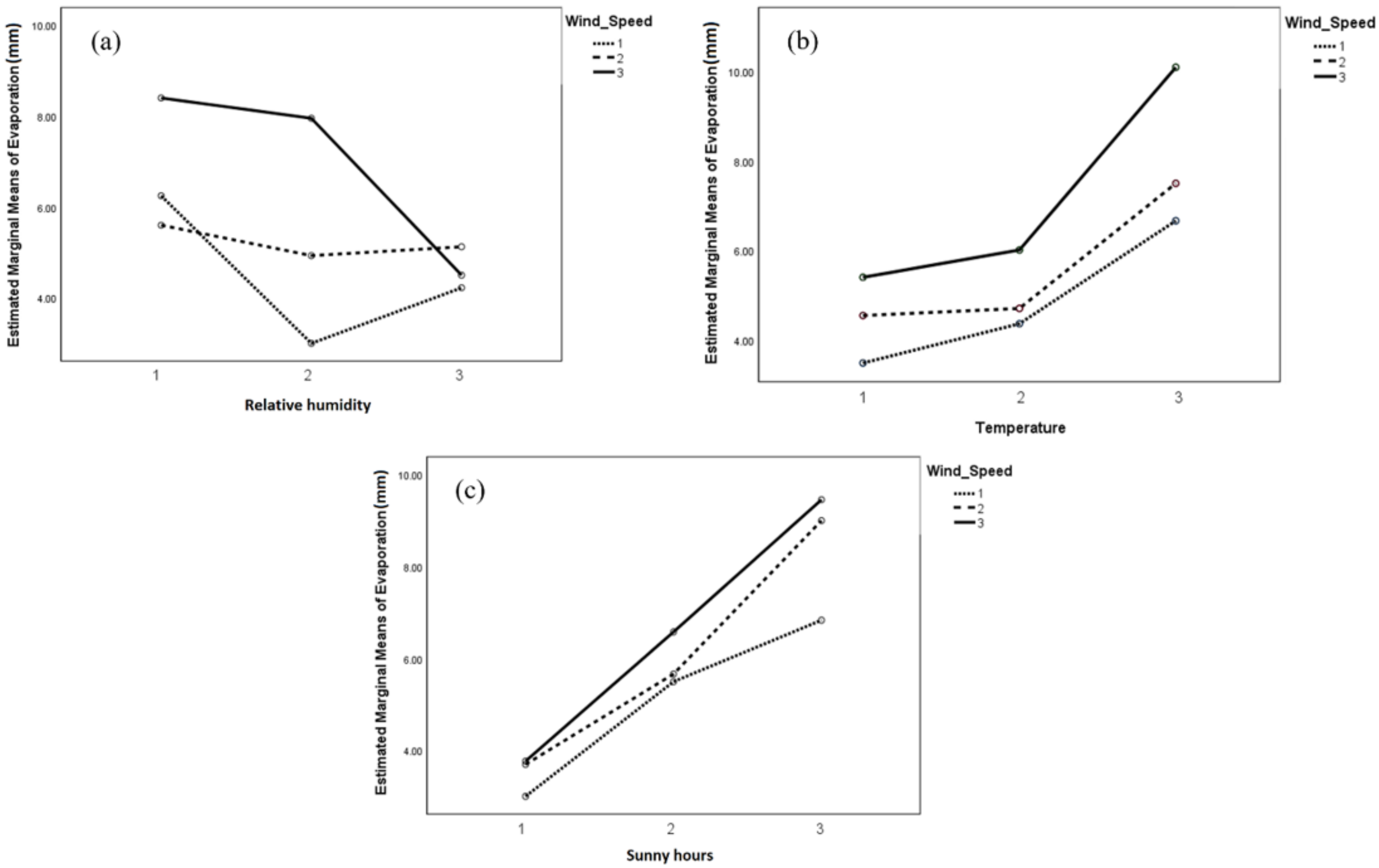

Figure 8

The effect of wind speed on evaporation rate by considering interaction effects