Lake Evaporation Mitigation Using Self-Assembled Films: Case Study Of Chitgar Lake

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Abstract

Evaporation is a significant outflow in water bodies and is the only outflow in man-made Chitgar Lake. It is estimated to be more than 2 million cubic meters annually. In order to mitigate this outflow, we investigated different kinds of self-assembled thickness films. They consist of six different combinations of stearyl and cetyl alcohols with additives including jojoba oil, stearic acid, and calcium hydroxide. The study has been done from July to August with two pairs of class A evaporation pans; one pair semi-floated on Chitgar lake water and another one located on the shore. The experimental results showed that a monolayer contained 3:1 stearyl to cetyl alcohols with 60% weight of calcium hydroxide had the best performance and could reduce evaporation up to 50% during its 3 days' lifetime. The study indicated that the films had no significant side effects on lake water pH, turbidity, and total suspended solids except slight increase in water surface temperature.

1 Introduction

Less than 3% of available water on earth is freshwater (Fitts, 2013) and its demand is vastly increasing (Ashoori et al., 2017; Boretti and Rosa, 2019; Pouladi et al., 2022). So, it is essential to conserve existing freshwater resources, especially in dry climate regions like Iran which 90% is arid and semi-arid (Oroud, 2015; Hassan and Peirson, 2016; Boazar et al., 2019). The average rainfall is less than one-third of global average (Madani, 2014) and more than half of the country's population is exposed to water scarcity. Two-third of the precipitation volumes evaporates before reaching rivers (Frenken, 2009) and average water evaporation is more than three times of the global (Abbaspour et al., 2009). Therefore, Evaporation reduction methods could be of great help to preserve water where evaporation plays an essential role in water resources management (Yazdanpanah et al., 2013; Sebbar et al., 2019; Elkatoury et al., 2020; Mohammadi et al., 2022).

Physical barriers and chemical films have been frequently recommended in evaporation mitigation studies. Physical structures such as shading (Alvarez et al., 2006), and floating covers in different shapes like Aqua-Cap (Yao et al., 2010), plywood floats (Benzaghta et al., 2013), hollow PET bottles (Simon K. et al., 2016), modular covers (Hassan et al., 2015) and floating plates and floating balls (Li et al., 2021) could be used on water body surface to diminish energy and mass exchanges between the water surface and the surrounding air. These technologies are suitable for use in water reservoirs which are less than 10 ha while chemical covers are recommended as an economical technique for large water bodies (Craig et al., 2007). In the chemical method, a nanometric monolayer consists of long-chain self-spread molecules is dispersed on water to form a molecular film, which prevents the water molecules from evaporating (Mozafari et al., 2019; Mohammadi et al., 2022). One tail of these molecules is hydrophilic that will settle on the water surface and another tail is hydrophobic which extends in the air-water interface thus they stand next to each other on the water surface and acts as a unique thin layer (Pittaway and Ancker, 2010).

One of the most common suggested chemical materials is fully saturated alkyl chains consisting more than 12 carbons with a polar group like long chain fatty alcohols such as stearyl or cetyl alcohols (Barnes, 2008; Mcjannet et al., 2008). They spontaneously spread on the surface and could decrease evaporation up to 45% on reservoirs and lakes which areas are less than 10 km^2 (Mcjannet et al., 2008). Also, evaporation reduction of the monolayers has been reported up to 70% in smaller scales and limited conditions such as in class A evaporation pans and lab scale tests (Gallego-Elvira et al., 2013; Mozafari et al., 2019). Using such layers are more reasonable than physical covers in periods that evaporation is higher and wind flow is not too heavy, since they display better stability on lower wind speed (Prime et al., 2012; Mozafari et al., 2019). Small amount of these materials are enough to cover wide area, for instance about 20 g of Stearyl alcohol is enough to cover a hectare. Although they have relatively short lifetime and may be degraded by microbial activities (Craig et al., 2005; Pittaway et al., 2015; Mohammadi et al., 2022), they are environmentally safe and cause less side effects on lake's water quality. Previous studies have shown using these materials has no effect on public health, aquatic life, water treatment and recreational use of lakes or reservoirs (bloodgood, 1959; Wixson, 1966; Wiltzius, 1967; Craig et al., 2005; Babu et al., 2010; Pittaway and Ancker, 2010; Mohammadi et al., 2022). They also don't affect lake's oxygen exchange with surrounding air (Mcjannet et al., 2008). Therefore, we have considered using these environmentally friendly materials to reduce water loss on Chitgar lake which has encountered problems due to evaporation.

Chitgar lake is the largest artificial recreational lake in Iran. It was designed to perform as a flood retention pond in 1960 but due to budget and water shortage problems, its construction has been postponed for decades and finally has been put into operation in 2013 for urban development and recreational activity (Akhshik et al., 2020). The only cause of water level drop in the lake is evaporation and has been estimated about two million cubic meters (MCM) annually (STPCEC, 2012). The Kan River is the only water supplier of the lake which is also directed toward agricultural lands in the south of Tehran and Fashafouyeh plain and finally flows into the Ali-Khan wetland (Skardi et al., 2020). The plain is in the critical situation of groundwater level (Bagheri et al., 2020), and Ali-Khan wetland has recently been exposed to drought and extinction. In another word, Chitgar lake is one of the water reduction sources of the river downstream (Khorasani et al., 2018), moreover, the high growth of algae due to eutrophication affects the recreational and utilization of the lake (Khorasani et al., 2018) is another main challenge that the lake is facing since the operation, and all of two challenges will be solved by reducing evaporation. This is especially becoming more important in summer when the most evaporation occurs and causes increase in phosphorous concentration that leads to algal bloom (Yan et al., 2019). In this case, reducing evaporation of the lake can help to solve eutrophication problem and save more water in drought conditions along with water shortage problems of Tehran (Madani, 2014; Ravanshadnia et al., 2015; Ardalan et al., 2019; Motlaghzadeh et al., 2020). The main purpose of this study is to evaluate the feasibility of using self-spread thin films containing long-chain molecules on evaporation reduction of Chitgar lake.

2 Method And Field Facilities

2.1 Site Description and Field Experiments

Chitgar lake is a large man-made infrastructure located in Iran's capital, as shown in Fig. 1. The area of water surface, the volume of reservoir, the maximum water depth and mean water depth at normal water level is 1.3 km^2, 7 MCM, 9.5 m and 5.4 m respectively (STPCEC, 2012). The lake has been designed to improve urban development, recreation, green space, and tourist attraction. The bottom of the lake is separated from the bed by geomembrane and is not connected to any groundwater source which can be considered as a closed lake. The lakes inflow comprised of seasonal rainfall and the Kan River while the only outflow is evaporation. The evaporation rate of the lake has been estimated to be higher than 8 mm/day in August (Behrouzi and Chini, 2016), hence it is implied during summer, about 1 MCM of water, equivalent to the water demand of a city with a population of about 100,000 people, evaporates.

Two pairs of standard class A evaporation pans were used for thin films application evaluation. They can be exposed either above the ground or mounted on floating platforms on water bodies (WMO, 2008). The water inside ground pans is stagnant while floating ones face waves and are turbulent which may better represent lake conditions. Therefore, we used two pairs of pans to study the effect of thin films on the water evaporation in wavy and still conditions; one pair placed in land and another semi-floated on the water surface as shown in Fig. 2. In each pair one pan covered with monolayer as the test pan and another one uncovered as the control pan. The most appropriate location for conducting tests was found to be in and around the middle island to meet World Meteorological Organization's standards, i.e., open air and airflow environment, away from any shading and mounted on wooden platform for land pans (G. Allen et al., 1998; WMO, 2008). Screens were mounted on all pans for preventing birds using pans water that will reduce pan's evaporation by 10% (G. Allen et al., 1998) which will have the same effect on all pans. At each stage of the experiment, all pans were first filled by the lake water to the depth of 20 cm based on the recommendation of standard usage of class A evaporation pan (G. Allen et al., 1998). Experiments have been conducted during 2019's summer in July and August and each of which continued for 3 days until the films have been degraded, moreover after this period the water table inside the control pans usually drops near the low limit of the standard which cause error (G. Allen et al., 1998). Water inside the pans cannot be replenished because of the monolayers break and drowning due to water infusion Assuming that the evaporation of the control and test pan are Δh_c and Δh_t, respectively, and R_i is the evaporation reduction percentage of the film i, the evaporation reduction percentage of each film can be calculated using the Eq. (1):

$$R_i = \frac{\Delta h_c - \Delta h_t}{\Delta h_c} \times 100$$

1

The water quality parameters including pH, turbidity and total suspended solids (TSS) of each pan were measured before and after each test by "Hack HQ40D", "LaMotte 2020 turbidity meter" and "Hack DR2800" probes, respectively, to determine the films effect on water parameters that may affect the recreational use of the lake (Keeler et al., 2015; Chang et al., 2020). Also, to investigate the effect of meteorological parameters on the behavior of the monolayers, air temperature and wind velocity were gathered online every three hours by selecting the lake location from “Dark Sky” corporation (DarkSky, 2019.) and the water surface temperature was measured on the field.

2.2 Film Formulation And Application

Different combination of Stearyl alcohol (St, $CH_3(CH_2)17OH$), cetyl alcohol (Ce, $CH_3(CH_2)15OH$), stearic acid (Sa, $CH_3(CH_2)16COOH$) and Jojoba oil (JO) materials were used to form a molecular film on water surface. St and Ce were selected based on their recommendation in past studies (Craig et al., 2007; Mcjannet et al., 2008; Prime et al., 2012) and they have chain length of 18 and 16 Carbons, respectively; Ce has a lower molecular mass than St and disperses more rapidly on the water surface, on the other hand, St provides a more robust film because of the longer carbon chains (Prime et al., 2012). Stearic acid is also a non-toxic fatty acid that have same chain length as stearyl alcohol (Zhen et al., 2015), and can improve the interaction between film molecules and the subfilm water (Brzozowska et al., 2012). Jojoba oil is a natural liquid (Matsumoto et al., 2019), comprised of mostly esters with chain length of 40 and 42 Carbons (Sánchez et al., 2015) that have high oxidant and temperature stability (Le Dréau et al., 2009; Sánchez et al., 2016) which can be used as evaporation mitigation material. Additives like Calcium hydroxide (CH) can be used to overcome practical films difficulties such as loss from water surface and low respreading rate (Barnes, 2008; Mozafari et al., 2019). Moreover, small amount of these materials are enough to cover the water surface and are available and economical which are presented in Table 1. Each molecule of St, Ce, Sa and JO cover 23 (Prime et al., 2012), 24 (Prime et al., 2012), 20 (Lendrum and McGrath, 2009), and 77 (Caruso et al., 2018) A^2 area on pure water surface in a monolayer of them, respectively. Considering the surface area and molecular mass, the required amount to form a monolayer (i.e. closely packed molecules) on the water surface can be calculated using the Eq. (2):

$$Monolayer\ Mass(g) = \frac{Total\ Area(cm^2)}{Area\ of\ one\ Molecule(\frac{A^2}{molecule}) \times 10^{-16}} \times \frac{Molecular\ weight(\frac{g}{mol})}{6.023 \times 10^{23}(\frac{molecule}{mol})}$$

2

For example, 1.91 mg of Ce is required to disperse a layer of Ce on a class A pan with an area of 1.14 m^2. In order to better disperse the monolayers on the water surface, they can be dissolved in a suitable volatile solvent such as ethanol. In this case, the solvent will evaporate in a short time and the thin layer will remain on the surface (Prime et al., 2012). The proper composition and materials weight of the film added to the solvent were found based on our laboratory scale tests results on fresh water and field experiments by evaporation pans contained Lake’s water. Used materials in each film is equal to sixty times the amount of fatty alcohols and acids required to form one monolayer of them, which total thickness is about 100 nm. They were prepared with 5 mg/ml concentration in ethanol as solvent and sprayed on each test pan. The calculated number and required mass of the corresponding molecular layers for each film used in this study are shown in Table 1.

3 Results And Discussion

Average evaporation reduction percentages of the film (R) that is expressed in Eq. (1) is shown in Fig. 3. for the First Day (FD), Second Day (SD) and Third Day (TD) besides the Total Water height saved by the film (TW), average air temperature (Tair) and wind speed (w) during the experiment. The F1 containing only St, presented approximately same R on the land and semi-floating pans about 25%, and could save its stability for 72 hr. Although R of land pan and floating pan are similar, the F1 on land pan could save 2 mm of water height more than on floating pan, because of higher evaporation in the land comparison to the floating pans which are in contact with lakes water. F2 containing only Ce with shorter chain length indicated less performance than F1 with R about 16% on each pan. This film also disappeared after the FD due to naturally faster degradation and easily broken down by bacteria (Craig et al., 2005), so it could save the least amount of water in comparison to the other films. JO as a long chain ester was mixed with St to make F3 film which could successfully reduce evaporation in the FD on land pan about 50% but didn't perform well on the floating pan (34%) due to collapsing of its film in wavy water and windy condition. So, a considerable drop was observed in both pans on the SD because of the first windy day. Since the floating pans experience waves inside, more cracks or holes will appear in the film, therefore using a component to fill in cracks and help respreading becomes important (Mozafari et al., 2019). In order to overcome this problem St and Ce can be mixed in which the shorter one (Ce) helps spreading rate and fill in the cracks and the longer one (St) acts more as an evaporation retardant (Prime et al., 2012). The F4 consists of 3:1 St to Ce showed higher R more than 50% for the FD in the higher air temperature about 34 ^{o}C in both pans, indicate closer molecular packing film and the synergistic effect. Its performance also increased for the SD bolding the filler role in windy conditions but reduced R in the SD is due to probable fast degradation of Ce which was approved after the F2 experiment and totally disappeared on TD. The F4 could save about 8.5 mm of water in both pans during three days, but to improve layers' performance on the surface and overcome Ce degradation, the Sa was added to the mixture to create F5 (Brzozowska et al., 2012). The F5 performed similar to the F4 in the FD on land pan but didn't do well on floating pan, although the air temperature was less. It also disappeared on the SD in the floating pan due to emerging into wavy water in windy condition (Brzozowska et al., 2012) and didn't achieve to save appropriate TW. In order to improve stability and increase spreading rate of the layer, the CH were added to F4 to make F6 (Mozafari et al., 2019) which indicated more than 50% R in the FD on both land and floating pans. The CH dissolves in the water and make positive charged Calcium ions that makes the F4 spread all over the surface because of positive repel force and can resist against wind up to 4.5 m/s (Waheeb Youssef and Khodzinskaya, 2019). Although the wind velocity reached 5 m/s on the SD, CH greatly helped layer to maintain its performance and could reduce evaporation about 80% of the FD on land and 90% on semi-floating pan, it also showed good stability on semi-floated pan on TD and decreased evaporation up to 34%. The F6 could save more than 12.5 mm of water during three days and was the most effective film for reducing evaporation. By using this film on lake water, it is anticipated to halve the evaporation and reduce it from more than 8 mm/day in summer to 4 mm/day, therefore saving about 5000 m^3/day of water. Considering the lake's real reaction to wind, each film should be applied at least each three days to continuously cover the surface and diminish evaporation.

The lake water quality parameters include pH, turbidity and TSS before each test was measured that their average values were 8.4, 4.5 (NTU) and 6.5 (mg/l) respectively. Their average values after each test compared to the beginning showed that the films had no significant effect on pH, but a decrease in turbidity and TSS were observed in all pans, which was normal due to stagnant water. The average differential values were about 0.2, 1.7 NTU and 1.2 mg/l for pH, turbidity and TSS, respectively. Evaporation mitigation films could increase water surface temperature which growth rate depends on the films functionality; for example, the F2 with least R showed almost no temperature difference and the best film (F5) showed 5 ^{o}C average difference in air temperature of 35 ^{o}C and lake water temperature of 29 ^{o}C and the overall average of all films is 3.17 ^{o}C.

4 Conclusion

The effect of self-assembled nanometric films on the evaporation of Chitgar lake was studied from July to August as a period with maximum evaporation in the year. The films were composed of cetyl (Ce) and stearyl (St) alcohols along with Jojoba oil (JO), stearic acid (Sa), and calcium hydroxide (CH). In order to investigate their performance, two pairs of Class A evaporation pan used; One pair placed on the lake's shore and the other pair floated on the lake. Evaporation of pans has been measured in the presence and absence of films for three consecutive days. Results showed that the film comprised of only Ce had the least performance on evaporation reduction and could save less than 2 mm of water in total. On the other hand, the film consists of 3:1 St to Ce with 60% weight of CH had the best performance on both land and floating pans. This film could mitigate evaporation up to 50% and maintain its stability for 72 hours in the presence of 5 m/s wind. In our case study of Chitgar Lake, these films showed no significant effect on water quality parameters such as pH, turbidity and TSS. The main finding of the current study indicated that using the optimized film and respread it every 3 days during summer, could reduce the lake evaporation about 0.5 million m^3 and save water for Ali-Khan wetland, Fashafouyeh plain and agriculture demand in downstream. Moreover, by reducing evaporation the concentration of the phosphorous materials doesn't increase, hence could help to suppress eutrophication of the lake.

Declarations

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Table

Table 1. number of monolayers (ML) and total required mass for each component of the films (g/m^2).

Film number	Stearyl alcohol (St)	Cetyl alcohol (Ce)	Stearic acid (Sa)	Calcium hydroxide (CH)	Jojoba oil (JO)
Film 1 (F1)	60 ML (0.12g/m^2)	-	-	-	-
Film 2 (F2)	-	60 ML (0.1g/m^2)	-	-	-
Film 3 (F3)	30 ML (0.06g/m^2)	-	-	-	30 ML (50mL/m^2)
Film 4 (F4)	45 ML (0.1g/m^2)	15 ML (0.03g/m^2)	-	-	-
Film 5 (F5)	30 ML (0.06g/m^2)	10 ML (0.02g/m^2)	20 ML (0.05g/m^2)	-	-
Film 6 (F6)	45 ML (0.1g/m^2)	15 ML (0.03g/m^2)	-	60% weight of total mass (0.2g/m^2)	-

Figures

Figure 1

Legend not included with this version.

Figure 2

Legend not included with this version.

Figure 3

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