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Review

Controversy over the Use of "Shade Covers" to Avoid Water Evaporation in Water Reservoirs

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Abstract: Water scarcity and sustainability are main current concerns affecting billions of people worldwide. Apart from policies designed to guarantee water supply, technologies and procedures have been developed to optimize the uses of water and water recycling as well as to minimize water scarcity. Among these technologies, those based on the use of bioinspired fibres, membranes, nanomaterials, liquid-liquid extraction methods using ionic liquids or approaches involving plants or microbes have been successfully carried out. One of the main problems associated with most of these technologies is the high cost of their implementation and maintenance. Consequently, other cheaper strategies have been explored, such as the use of shade covers. The objective of this work is to summarize the most recent findings on the use of shade covers (suspended shade cloth covers and shade objects) on water reservoirs, mainly agricultural water reservoirs (AWRs). Reflections on the investment-benefit relationship of this technological proposal are also herein discussed. Apart from traditional shade cloth clover, more recently, other covers like shade balls/squares/hexagons (shady objects) have also been proposed as promising approaches to save water and keep its quality. However, the manufacturing of shady objects, mainly made of polyethylene plastic, results in: (i) high cost (high energy cost and use of raw materials like crude oil and natural gas); (ii) significant production of residues, and (iii) visual environmental pollution. The main conclusion reached from this review is that the controversy over the use of shade covers continues in the spotlight of scientists, water managers, and related companies; although this approach saves water and prevents water quality deterioration, a large number of recalcitrant residues are produced, not only during their production, but also when they must be replaced due to deterioration.

Keywords: shade cover; shade balls; water evaporation; water quality; microbial bloom; water reservoirs; water sustainability

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1. Introduction

The concept "water sustainability" is currently related to approaches that efficiently provide safe, reliable, and easily accessible water as well as reliable sanitation and waterways protected from pollution. Sustainability also means being resilient and adaptable to extreme weather events that may contribute to issues such as flooding and scarcity [1]. Thus, the sustainability of hydric resources depends on human practices, soils moisture, climate (mainly temperatures and precipitation cycles), evapotranspiration flows and surface runoff [2]. The availability of high-quality water for human consumption and agriculture is one of the major concerns worldwide [3]. Climate change, among other factors, is affecting the water supply in several regions, in turn affecting millions of people. Thus, some studies reported in 2016 stated that half a billion people in the world face severe water scarcity all year round [4]. Globally, water scarcity is particularly acute in certain regions like Africa, Mediterranean regions, the Middle East, as well as the western states of America [5,6]. It is pervasive even in water-rich areas due to the significant pressure created by the burgeoning human population, industrialization, civilization, environmental changes, and agricultural activities. The problem of access to safe water is currently inevitable and requires tremendous research to devise new cheaper technologies for purification of water, while considering energy requirements, environmental impact, and global policies [7]. Water scarcity, which encompasses both water availability and water quality, is an important indicator of health and is also associated with inadequate access to clean water and sanitation. Therefore, it afflicts societies and ecosystems [4,8–10]. Consequently, anticipating water shortages is vital because of the indispensable role of water for life. Water quality and scarcity assessment is an important basic work in the development, utilization, management, and protection of water resources, and a prerequisite for water safety [11].

In this context, monitoring of water scarcity metrics reveals essential to deal with water management. Metrics of water scarcity have evolved over the last three decades from simple threshold indicators to holistic measures characterizing human environments and freshwater sustainability [12]. Metrics usually evaluate renewable freshwater resources measuring mean annual river runoff, which masks hydrological variability, and quantify subjectively socio-economic conditions characterizing adaptive capacity. Several authors have stated that there is a relevant absence of research evaluating whether these metrics of water scarcity are meaningful and proposed that the measurement of water scarcity must be redefined physically in terms of the freshwater storage required to address imbalances in intra- and inter-annual fluxes of freshwater supply and demand [12]. Besides, those authors suggested to abandon subjective quantifications of human environments and to use the measurement of water scarcity to inform participatory decision-making processes that explore a wide range of options for addressing freshwater storage requirements beyond dams that include use of renewable groundwater, soil water and trading in virtual water [8,12]. Consequently, addressing future challenges will require a combination of new technological development in water storage/purification/desalinization and environmental remediation technology with suitable conservation policies [13–16]. Although desalinization remains one of the most expensive ways to produce potable water, water scarcity also forces populations to find new sources of drinking water; therefore, scientists are developing innovations that may soon make desalination a reasonable option for many more communities [15,17–19]. Among the most recent technologies and methodologies described to optimize the uses of water, water recycling as well as to minimize water scarcity the following can be highlighted (Table 1):

Table 1. Examples of the most recent technologies and procedures aiming water treatment/recycling or improving the use of water.

Technology-Objective	References
Design bioinspired fibres for water collection (inspired by spider silk)	[20–22]
Nanomaterials or bioinspired materials for water purification and decontamination	[7,13,23–25]
Membranes and biomembranes to treat and re-use water from industry, waste streams and groundwaters	[16,26–28]
Liquid-liquid extraction procedures using ionic liquids to decontaminate water.	[29,30]
Phytodepuration, microbial films or plant-based natural compounds (like coagulants) for water treatments.	[31–33]
Physical, operational, chemical, and structural methods to mitigate water evaporation (Destratification, chemical monolayers, shade covers, etc.)	[34–39]

Regarding processes used for avoiding water loss or preserving its quality in water reservoirs, those approaches based on the concept of "shade covers" are worth mentioning. Shade covers are structural methods including physical structures like floating materials to minimize energy and mass exchanges between the water surface and the surrounding air [40], shelters that protect the water body from wind [41] or shading screens which minimize the incoming radiation and wind speed over the water surface. These approaches have been explored worldwide with special emphasis in arid and semiarid geographical regions like Spain [37]. The main objectives of these technologies are to minimize the evaporation of water and to prevent deterioration of the quality of water (mainly avoiding algal blooms). However, their implementation (including time and economical cost), potential negative environmental impact as well as benefits and global efficiency are far from known accurately from a scientific point of view. This work summarizes the most recent findings on the use of shade covers (suspended shade cloth covers and shade objects) on water reservoirs, mainly agricultural water reservoirs (AWRs). AWRs are commonly used to guarantee water supply throughout the whole irrigation season in arid and semiarid areas. In these systems, an important fraction of the total stored water is lost through evaporation each year, substantially decreasing overall irrigation efficiency. For this reason, great effort is being done to reduce water evaporation and other collateral effects like the bloom of microorganisms and algae which decrease the quality of water (particularly during periods like spring or summer with high solar radiation and high vapor pressure deficit). In addition, some reflections on the investment-benefit relationship of this technological proposal are herein discussed.

2. Suspended Shade Covers

Among the structural methods, suspended shade cloth covers (SSCCs) have been highlighted during the last two decades as one of the most promising techniques to avoid water evaporation [35,39]. SSCCs are tarps of different colours (usually made of black polyethylene) covering water reservoirs (Figure 1). Usually, the shade cover is suspended above the water surface by means of a high-tension polyamide cable structure [35]. The cables are both above and below the cloth to hold the mesh and to prevent wind suction. SSCCs reduce solar radiation and wind speed while increasing the air humidity under the cover [35].

Figure 1. Example of suspended shade cloth covers (SSCCs) used to cover water reservoirs to avoid water quality deterioration and evaporation. The covers are usually suspended a few centimetres above the water reserves. **Left**: black shade cloth cover (small pore size); **Right**: green shade cloth cover (medium pore size).

These covers are strong, durable, and resistant to tearing and rotting and allow airflow trough. Temperature on the surface of the water reservoir covered by these shade covers could increase, mainly when using black shade cloth covers. Field investigations on the effects of shade covers on water quality and evaporation have been limited by (i) environmental parameters like wind and wave turbulence, and beaching [34,37–39], and (ii) factors related to the cover as colour, porosity, and reflectivity. The main limitations observed in field investigations were the increase of the water temperature, low half-life of the materials used to make the cover (commonly replaced each natural year) and the time required to install them on the reservoir. SSCCs were one of the first approaches used to evaluate the decrease of water evaporation and the maintenance of water quality from AWRs in the southeast of Spain, for instance [34,35].

Although the number of studies on the efficiency of these covers is still scarce, all of them demonstrate a reduction of water evaporation rate close to 85%, as well as a dramatic limitation of algal blooms [34]. In some studies, the use of the SSCCs has been combined with the addition of a monolayer made of compounds like cetyl or stearyl alcohols, which spontaneously self-spread over the water surface and create a film one molecule thick. Although the monolayer was selectively toxic to some phytoplankton, did not increase water temperature, humified dissolved organic matter, or the biochemical oxygen demand, and did not reduce dissolved oxygen. Consequently, the impact of a monolayer on water quality and the microlayer may not be as detrimental as previously considered [37–39]. Monolayers usually provide moderate evaporation reductions (10–40%). However, they are a low-cost measure best suited to large AWRs (>10 ha in area) [35].

3. Shade Objects (Balls/Squares/Hexagons)

Shade objects are small plastic spheres, squares or even hexagons floating on top of a water reserve for environmental reasons. The creator of shade balls in California originally used them to prevent chemical treatments in the reservoir from reacting with sunlight creating bromate, which is a carcinogen regulated by many institutions worldwide (chlorine plus sunlight turns bromine into bromate that is a potentially cancer-causing agent; because shady objects stop bromate from forming below, less chlorine is required to treat the water than without them). More recently, other environmental issues have been associated to the use of shade objects: slowing down water evaporation, preventing algae blooms, avoiding birds landing on bodies of water and promote water heating.

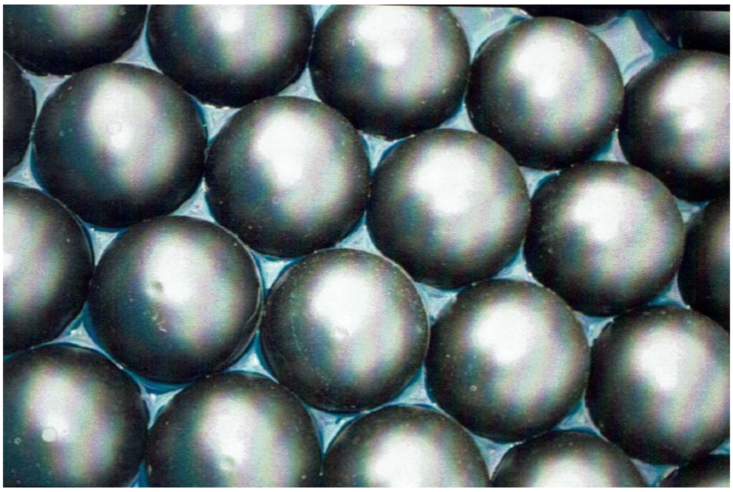
These objects are usually made of black high-density polyethylene (HDPE) (also called alkathene or polythene), which is a thermoplastic polymer produced from the monomer ethylene showing desirable properties, which are ideally applicable not only for potable water containers or pipes, but also wastewater. HDPE is commonly recycled and has the number "2" as its resin identification code [42,43]. The density of HDPE can range from 930 to 970 kg/m^3 and it is characterized by the following parameters: melting point: 130.8 °C; temperature of crystallization: 111.9 °C; latent heat of fusion: 178.6 kJ/kg; thermal conductivity: 0.44 W/m. °C; specific heat capacity 1330 to 2400 J/kg-K; specific heat (solid): 1.9 kJ/kg. °C and crystallinity: 60%. HDPE is resistant to many different solvents and compared to LDPE (low-density polyethylene) is harder, opaquer and can withstand somewhat higher temperatures (120 °C/248 °F for short periods) [44].

SSCCs and tarps show low half-life compared to shady objects (1–2 years vs. 15–20 years), can be expensive and metal coverings can take too long to install. For this reason, shade objects focused the attention of scientist, companies, and water management institutions at the end of last decade. Shade balls are usually used as free-floating elements (individual units that float on the water surface, partially shade the water surface, reflect the incoming solar radiation, and act as physical barriers that hinder the escape of water), whilst squares or hexagons can be used as free-gloating elements or as continuous floating cover (these are materials "sheets" that float on the water surface and cover "shade" the water surface) [45].

The main features characterising shade balls, squares and hexagons are described as follows:

3.1. Shade Balls

Shade balls are probably the most used shady objects at the time of writing this review. They are around 4 inches (10 cm) in diameter and usually partially filled with water to avoid being blown by wind (Figure 2) (although the second generation of shade balls are heavier than the original balls to provide higher weight instead of gaining weight by filling with water). The manufacturers that sell them as high-performance floating cover highlighting the following benefits and advantages: adjust to variation of the liquid level by spreading and stacking; allow movement of equipment through liquid; water evaporation is reduced up to 90%; deter waterfowl from landing on covered waters (their round shape avoid birds landing, so no feather-borne diseases get in the water); balls are UV resistant and back balls reduce penetration of UV rays (this limiting growth of algae and clogging weeds); fast and effective solution to odour problems (this property allows their use on other reservoirs like those containing purines or industrial wastewaters); heating cost reduced by up to 75%; reduce chemical reactions between products dissolved in water; unaffected by rain water; cheap maintenance; quick and simple to install. Finally, manufacturers state that the balls are made of recyclable plastics, so they can go on to be reused for other purposes once they are removed from the reservoirs. Because of their arc structures, the floating balls are unstable in the wind and waves, which is one of the main disadvantages of these objects because it reduces evaporation suppression efficiency (ESE).



(**A**)

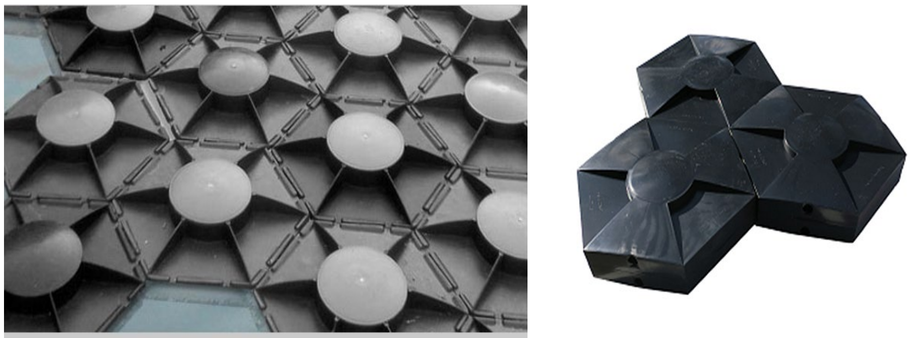
(**B**)

Figure 2. Example of shade balls in a domestic water reservoir located in a countryside house (Southeast of Spain). Small experiment carried out by the author during summer 2014. (**A**) Shade balls; (**B**) Small pool covered by shade balls.

A small experiment using shade balls was carried out by the author in collaboration with "Panal Flotante Company" (Alicante, Spain; https://www.panalflotante.com/, (accessed on 20 April 2021)) in which three pools (control without shade balls and two pool covered by black shade balls) where monitored during the summer of 2014 (June–September) (Figure 2). Parameters like pH, conductivity, turbidity, rate of water evaporation, nitrates, nitrites, ammonium, COD (Chemical Oxygen Demand), BOD (Biological Oxygen Demand) and optical density at 600 nm were measured twice per week (unpublished data). Parameters related to climate (rain, temperature, and wind) in this region during the period in which the experiments were carried out were obtained from the closest meteorological station, (https://www.meteovillena.es/, accessed on 10 August 2014); Villena (Alicante, Spain). Optical microscopy was also used to check the samples taken from the pools each two weeks. This study stated that water in covered pool was almost transparent and without organic matter after 4 months of monitorization. However, water from uncovered pool contained small pieces of leaves, small stones, and sand. Besides, water evaporation rates decreased up to 90% when comparing covered and non-covered pools.

3.2. Shade Squares and Hexagons

Hexagonal or squares floating cover system ensures coverage of up to 99%, which is the main advantage comparing them with shade balls (Figure 3). Consequently, the reduction of water evaporation and the water exposition to light is even more efficient compared to shade balls (lower penetration of UV rays which avoids growth of algae, and clogging weeds).



(**A**)

(**B**)

Figure 3. Examples of squares or hexagons used as shade objects. Different models are available at global market. Pictures taken from https://www.awtti.com/hexprotect-cover-floating-cover/, (accessed on 20 April 2021); http://megaplast.cl/sistema-de-cubiertas-flotantes-para-control-emisiones-evaporacion-y-olores/, (accessed on 20 April 2021); http://murciadiario.com/art/14721/evapo-control-reduce-la-evaporacion-en-embalses-y-balsas-de-riego-mas-de-un-80, (accessed on 20 April 2021). (**A**) Examples of hexagons. (**B**) Example of squares-based cover.

Another important advantage is the improvement of odor prevention (it justifies the use of these objects to cover water reservoirs containing industrial waters) as well as their management: as a consequence of their shape, they do not represent an obstacle to static, moving or dipping equipment. The squares/hexagons will keep up with liquid level, rising, lowering and restacking themselves as needed. Consequently, the installation of these objects in the reservoirs minimizes the use of labor, avoids repair and maintenance costs are lower than those derived from the use of shade balls and SSCCs.

4. Benefits of the Use of Shade Covers vs. Overall Cost of Their Manufacturing and Potential Environmental Damages Produced

Although the number of research studies on the efficiency and environmental impact of shade covers is still scarce, most of the results reported so far demonstrate that this methodology significantly reduces water evaporation and contributes to the maintenance of water quality [35]. Several accurate studies carried out in the southeast of Spain (Segura River Basin, Murcia) and other semiarid and arid regions in China, USA, Egypt, Brazil, or Australia have demonstrated that SSCCs can mitigate relevant evaporation losses and save water for irrigation purposes (up to 84% evaporation reduction has been achieved in AWRs) [35,45].

Shade balls were supposed to save water from the very beginning of their use, even more efficiently than SSCCs. Nevertheless, several scientists and journals have already stated few concerns about them as following summarized. As an example, to understand this controversy, the water reservoirs in several cities of California state can be considered.

In 2008, the Los Angeles Department of Water and Power (LADWP) proposed the use of shade ball (around 400,000 balls) in the Ivanhoe reservoir with the main objective of saving water and preventing the formation of a carcinogenic chemical, bromate. The reduction in evaporation led to an estimated savings of about 1.1 billion litres (290 million gallons) of water in one year. Few years later, other water reserves were also covered by black shade balls made of HDPE, not only in United States but also in Spain and Middle East countries. However, the balls used in this period required 2.9 million cubic meters of water as well as oil, natural gas, and electricity to make polyethylene required in their manufacture (1000 lbs of polyethylene = 188 lbs of oil and 827 lbs of natural gas and 159 kWh of electricity). Some estimations indicate that shade balls needed to be used for about three years to recover the water used for their manufacturing. Considering examples like Los Angeles Reservoir in Sylmar, California, the shade balls conserved 300 million gallons of water each year. In this case, 96 million of balls were used accounting for an overall cost around $34.5 million. Each single black ball costs approximately 40 cents, thus making it an apparent cheaper solution than alternatives such as dividing the reservoir into two parts with a dam and installing floating. Besides, the plastic used to make them (mainly HPDE) is of food-grade plastic and can be recycled after the replacement of deteriorated balls. Therefore, the controversy becomes thus: are shade objects cheaper than shade cloth covers or roofs? Are those systems equally efficient saving water from evaporation and maintaining water quality? Balls have a lifespan of ten years versus 2–3 years in the case of shade cloth covers. What is the most environmentally friendly and most economically efficient strategy? Are these technologies economically feasible? Although several studies revealed that the use of the balls and SSCCs is economically visible, their economic efficiency is still an open discussion [45].

In 2018, after a decade of shade balls use in USA, and analysing the reservoir of drought-embattled Los Angeles (96 million floating plastic "shade" balls were dumped into it), researchers from Imperial College London in the UK, MIT in the US and the University of Twente in the Netherlands calculated the volume of water used to make the balls and the volume of water saved from evaporation. The main conclusion was that manufacturing of plastic balls needed more water than it saved. Regarding to other environmental concerns related to the used of shade covers, the following have been stated:

1. Negative visual impact is related to shade covers, because in general people are never going to be comfortable with the idea of millions of plastic objects floating on potable water reservoirs. This effect is like the one related to plastic greenhouses.
2. Potential production of endocrine disrupting chemicals like bisphenol A (BPA) (most plastics leach endocrine disrupting chemicals that interfere with animal and human hormone systems [46,47]. These chemical compounds mainly appear if plastics are left in the water and exposed to sun over a long period (average of 10 years).
3. Potential production of microplastics. Most plastics found in aquatic environments normally start out as larger objects (like plastic bags and toothbrushes). Over time, they fragment into tiny microplastics. 92% of the 5.25 trillion plastic pieces floating on the surface of oceans are smaller than a grain of rice because plastics do not decay into their constituent molecules like organic substances. Instead, they fragment into smaller bits that could be ingested through sea food or the water we drink [48,49]. This could be the case for shade objects floating on water too. Although microplastics have been detected in continental waters and freshwater reservoirs [50], studies about the potential production of microplastics from shady objects are yet to come.

Apart from these concerns, several studies state that compared to structural methods (also known as physical covers), technologies like the evaporation suppression efficiency (ESE) and durability of the chemical and biological solutions were lower. However, despite the evidence that shade covers provide benefits in water management and storage, the environmental impacts of their manufacture, use and recycling remain in question.

5. Conclusions

It has been concluded that around 50% of the capacity of global water reservoirs is lost by evaporation, affecting their function of ensuring water availability and sustainability [45]. Over the decades, several technologies based on biological, chemical, and physical barriers were developed to minimize water evaporation, mainly in agricultural water reservoirs (AWRs) located in arid and semiarid areas, thus ensuring water supply for crop. The efficiency and applicability of these barriers are still a matter of discussion, given their economic efficiency, environmental consequences, and operational difficulties are accounted for. In principle, suspended shade covers have revealed as a promising alternative to other technologies aiming the maintenance of water quality and minimizing evaporation rates. Recently, other covers like shady object have also been proposed as efficient tools to save water and keep its quality. Among the main benefits of using shady objects, two can be highlighted: the decrease of evaporation rates and de increase of water quality due to the inhibition of microbial blooms or the production of carcinogenic compounds. The manufacture of these floating covers is currently a booming industrial market worldwide. Although companies manufacturing shady objects defend their efficiency saving water as well as their low cost and long lifespan, some scientific reports demonstrated that the investment required for their production in terms of raw materials, water and energy is significant. In summary, controversy on their use must be dilucidated. Meanwhile, the scheme of saving water in one place by using more water elsewhere could have environmental impacts that were not considered during the original planning phase of the use of shade objects (solving one problem somewhere creates a new problem elsewhere). Consequently, more outdoor research must be developed in this field at a large scale (reservoirs scale) to identify and quantify benefits and damages of these strategies managing water storage. Finally, the latest developments in natural polymers free of by-products such as bisphenol [51], as well as the possible use of new developments in biodegradable polymers for the manufacturing of shade covers must be considered. In this context, the production of biodegradable polymers like PHAs (polyhydroxyalkanoates) using microbes like bacteria and archaea as cell factories [52] reveals a new natural source of bioplastics which has potential uses in this area.

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