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Article

Slowing ice melting from thermal radiation using sustainable, eco-friendly eggshells

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SUMMARY

Increased ice melting in the Arctic region has raised the atmospheric temperature, leading to more natural disasters, such as a growing number of wildfires in the western United States, which threaten human health and the environment. Safe and immediate solutions to prevent or at least slow ice melting will be critical in reducing natural disasters. Here, we investigated eco-friendly eggshells as thermal barriers to delay ice melting. By using a homemade environmental chamber, we determined that the thickness of materials is crucial in delaying water heating rather than their surface color. Moreover, multiple layers of crushed eggshells placed on top of iced water effectively reflected thermal radiation, delaying the time of ice melting by ~40% compared to the control without the layers. The eggshell layers also decreased the average water heating rate by ~30%, making them an effective thermal barrier. Since numerous eggshells are produced as waste worldwide, an eco-friendly, sustainable, and feasible thermal barrier can be prepared by repurposing them. In the future, deploying the eggshell layers in the Arctic region could contribute to slowing ice melting, which can cool the atmospheric temperature, reduce the number of natural disasters, such as wildfires, and eventually protect human health and the environment.

INTRODUCTION

Wildfires have become a growing threat to human health and the environment, which has been more evident in recent years, especially in the western United States. The frequent wildfires result from a hotter and drier climate, intensified by a phenomenon known as a heat dome, which the melting Arctic Sea ice has worsened (1, 2). Approximately 13% of Arctic Sea ice is lost per decade due to excess radiation combined with the natural solar radiation emitted to earth (3-6). This excess radiation originates from solar radiation previously trapped by the accumulation of carbon emissions in the atmosphere (5, 6). As a result, the increased radiation rapidly melts the sea ice, heating the ocean and atmosphere and leading to the creation of heat domes. Consequently, this exacerbates the associated natural disasters, including wildfires (**Figure 1**) (2).

Scattering or reflecting incoming radiation are major strategies to prevent ice melting (7-11). Current methods include injecting aerosol particles into the stratosphere, brightening marine clouds, and applying microbubbles on the surface of the ocean (7-11). Injecting aerosol particles in the stratosphere scatters and decreases solar radiation (7, 8). Brightened marine clouds reflect solar radiation from the lower atmosphere where stratocumulus clouds form (9, 10). Modifying ocean albedo using microbubbles scatters and reflects solar radiation back to space from the surface of the sea (11). While these approaches can be adapted as permanent solutions, an evaluation of their side effects and effective deployment techniques remains essential, which will take time to fully realize their potential. Meanwhile, continuous ice melting significantly increases the likelihood of natural disasters, such as wildfires, and threatens human health and the environment. Until those potential permanent solutions are fully researched and made available for use, safe and immediately applicable mitigation methods need to be developed and utilized, even if they may be temporary.

In our daily lives, thermal barriers play an important role in maintaining indoor temperatures by shielding against external heat or cold. Inspired by this concept, we explored the potential of deploying materials as thermal barriers on the ocean surface to mitigate radiation, thereby cooling the ocean and slowing the melting of sea ice. Key material parameters for an effective thermal barrier potentially include surface color, material composition, and geometry. Given that these materials would be used in marine environments, it is imperative that they are environmentally benign. Furthermore, for practical deployment, these materials must also be cost-effective and sustainable. These criteria led us to identify a material that meets all these requirements and has the potential to slow ice melting.

Eggshells, an eco-friendly material, emerged as a promising material candidate that aligned with our established requirements. We hypothesized that the white inner surface of eggshells and specific eggshell-based structures on water effectively reflect thermal radiation and delay or prevent ice melting. To test the hypothesis and evaluate eggshells as a thermal barrier, we established two research objectives. The first objective was to elucidate the relationship between water heating and design parameters of materials, such as surface color and material thickness. The second objective was to implement the results from the first research objective and identify eggshell geometries that would effectively reflect thermal radiation and mitigate ice melting in water. We

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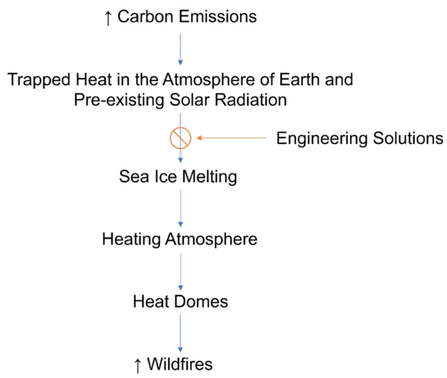

Figure 1. Chain reaction of how the accumulation of carbon emissions in the atmosphere increases natural disasters. Increased carbon emissions have worsened natural disasters that threaten human health and the environment. Potential engineering solutions can be kicked in to stop or delay one of the process components, such as sea ice melting, to prevent or slow the adverse reaction.

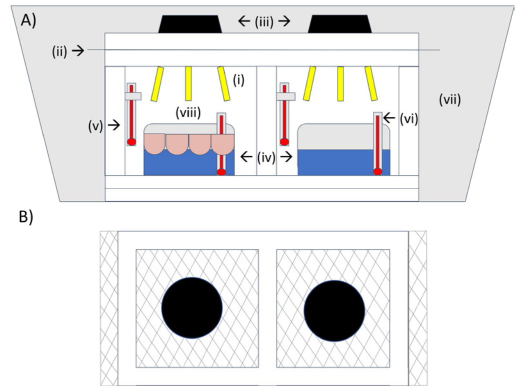

Figure 2. Schematic of the homemade environmental chamber. A) Cross-section view of the environmental chamber including (i) Styrofoam box with two testing chambers; (ii) Styrofoam lid with steel sheet with mesh; (iii) heat lamps; (iv) storage containers filled with salt water in each testing chamber (note: ice was placed in the water when needed); (v) thermometer measuring the air temperature; (vi) thermometer measuring the in-water temperature; (vii) tote box; and (viii) an example of hemispheric eggshell layer. **B)** Top view of the Styrofoam lid with heat lamps placed on top of the meshed steel lid.

found that the geometry of materials, such as thickness, as opposed to surface color, was crucial to the performance of the eggshell thermal barrier. Especially, we discovered that four stacked layers, referred to as a quad-layer, of crushed eggshells on water effectively delayed ice melting. Given the global abundance of eggshells, repurposing them offers an eco-friendly and sustainable solution for mitigating the impact of climate change on the Arctic region. We anticipate that this approach can help reduce the frequency of natural disasters, such as intense wildfires, and protect human health and the environment.

RESULTS

To understand materials parameters that are critical to reduce water heating and ice melting, we investigated the impact of surface color and material geometry, such as thickness, on the reflection of thermal radiation using a homemade environmental chamber (**Figure 2**). Prior to examining eggshells as a potential thermal barrier, we first studied how surface color influences reflecting radiation by comparing thin white and black tablecloths, known to reflect or absorb all wavelengths of visible light, respectively. We placed the tablecloths on the water surface and measured the relative temperatures each hour, calculated as the difference between the current and initial temperatures ($T_{t=1,\ 2,\ 3\ldots,8\ hrs} - T_{t=0\ hr}$; details in the Methods section) (**Figure 3A**). At 7:30 – 8:20 hours (details in the Methods section), relative in-water temperatures were 8.00 ± 0.71°C for the black-colored tablecloth (mean ± standard error of the mean, SEM), 8.47 ± 0.26°C for the white-colored tablecloth, and 7.59 ± 0.39°C for the control with no tablecloth (**Figure 3B**). There was no statistical significance when comparing data obtained from water in the absence or presence of black (p = 0.591) or white (p = 0.087) tablecloth. Therefore, we concluded that the thin tablecloth, regardless of its color, was not effective at reflecting thermal radiation.

Due to the limitation of affording varying thicknesses of tablecloth and to understand the relationship between the thickness of materials and reflection of thermal radiation, we used thick white- or black-colored Styrofoam floated on water (**Figure 4A**). At 7:30 – 8:20 hours, relative temperatures of water with the black and white Styrofoam were 5.72 ± 0.39°C and 6.17 ± 0.22°C, respectively (**Figure 4B**). Comparing relative in-water temperatures for black Styrofoam and the control showed statistical significance (p < 0.01, **Figure 4B**). Comparing white Styrofoam and the control also resulted in statistical significance (p < 0.01, **Figure 4B**). However, relative temperatures of water between black-colored and white-colored Styrofoam did not show statistical significance (p = 0.342). Based on the results, we concluded that the thickness of materials is a more important factor than surface color when reflecting thermal radiation.

Although Styrofoam demonstrated the ability to slow water heating, its negative environmental impact made it a less favorable option. Consequently, after identifying the critical design parameters of thermal barrier materials, such as geometry, particularly thickness, we constructed eco-friendly eggshells with diverse structures that effectively reflect thermal radiation from the water surface. Hemispheric and crushed eggshell layers served as the two geometrical variants in the water heating test (**Figure 5A**). We prepared the hemispheric eggshell layer by bisecting eggshells to retain a dome-like structure and connecting them side-by-side using adhesives, aiming to explore the effects of a curved surface on reflecting thermal radiation. Conversely, crushed eggshell layers, composed of fragmented eggshell shards, allowed for stacking multiple layers on top of a thin tablecloth. Due to the sinking nature of crushed eggshells without adequate support and the established ineffectiveness of tablecloth compared to the control, we utilized tablecloth to support the crushed eggshells (**Figures 3-5**). This setup was beneficial for assessing the impact of increased layering on thermal barrier properties. At 7:30 – 8:20 hours, relative temperatures measured from the water with the crushed eggshells in a single layer and hemispheric eggshells reached 6.65 ± 0.41°C and 7.37 ± 0.07°C, respectively (**Figure 5B**). The crushed eggshell layer and the hemispheric eggshell layer did not show statistical significance compared to the control, which did not include any covers on water (p = 0.172 and 0.576, respectively). Although there were no significant effects of

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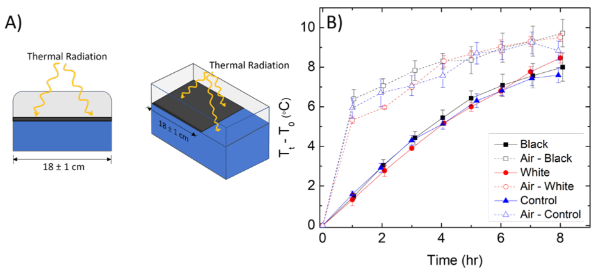

Figure 3. Impact of tablecloth color on reflection of thermal radiation. A) Black-colored tablecloth of < 1 mm thickness covered approximately two-thirds of the water surface inside the testing chamber. White-colored tablecloth (not shown in the schematic) also followed similar orientation as the black one depicted. **B)** Relative temperatures of water presented as a function of time ($T_{t=1,\ 2,\ 3\ldots,8} - T_{t=0}$) in the presence of black and white tablecloths, as well as no cover on water. Data shown of mean ± SEM, n = 7, 3, 14 for black, white, control, respectively.

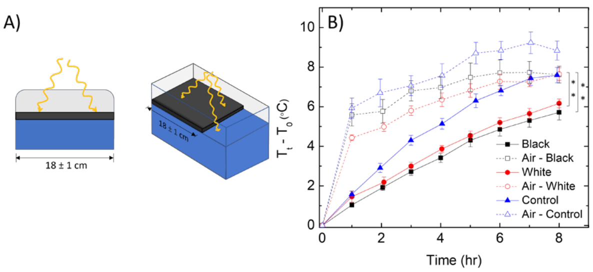

Figure 4. Impact of Styrofoam thickness on reflection of thermal radiation. A) Black-colored Styrofoam with ~2 cm thickness covered approximately two-thirds of the water surface. White-colored Styrofoam (not shown in the schematic) also followed similar orientation as the black one depicted. **B)** Relative temperatures of water presented as a function of time ($T_t - T_0$) in the absence or presence of black-colored or white-colored Styrofoam. Data shown of mean ± SEM, n = 6, 3, 14 for black, white, control, respectively; $^{**}p < 0.01$.

reflecting thermal radiation using eggshells, the mean of the relative in-water temperature of the crushed eggshell layer on tablecloth differed by ~1°C compared to the control (**Figure 5B**). Interestingly, despite the tablecloth alone raising the temperature more than the control, the crushed eggshells effectively counteracted this temperature rise (**Figure 5B**). Since the single-layer of crushed eggshells reduced the rise in water temperature and thicker materials can reflect thermal radiation more effectively, we decided to modulate the number of layers of crushed eggshells (**Figures 3-5**). We preferred this approach over hemispheric eggshells, which sank when layered and introduced an additional variable of air pockets inside and between the hemispheric eggshells.

To examine the relationship between the number of eggshell layers and water heating, we prepared single-, double-, triple-, and quad-layers of crushed eggshells on water (**Figure 6A**). The results at 7:30 – 8:20 hours showed that the relative in-water temperature for the control, resulted in 7.59 ± 0.39°C, while relative temperatures with the single-, double-, triple-, and quad-layers were 6.65 ± 0.41°C, 6.43 ± 0.62°C, 6.40 ± 0.42°C and 6.13 ± 0.34°C, respectively (**Figure 6B**). The means of relative temperatures decreased with increasing number of layers, but only the quad-layer of eggshells resulted in statistical significance compared to the control ($p < 0.05$, **Figure 6B**). Relative air temperatures at 7:30 – 8:20 hours for the single-, double-, triple-, and quad-layer of crushed eggshells were 7.82 ± 0.54°C, 8.70 ± 0.65°C, 8.68 ± 0.41°C, and 8.16 ± 0.55°C, while the control was 8.84 ± 0.48°C. No statistical significances were present between relative air temperatures among all data (p = 0.723, 0.189, 0.111, 0.342, respectively, **Figure 6C**). Based on the results, we concluded that the quad-layer of crushed eggshells effectively slowed water heating and would be the best option to test how long ice melting in water can be delayed under thermal radiation.

Since covering the whole water surface with the eggshell layer may be unrealistic in future large-scale, real-world applications, full coverage of the water surface was intentionally halved when testing the delaying effect of the quad eggshell layer on ice melting (**Figure 6A, 7A**). We measured the changes of in-water and air temperatures over 8.5 hours. From t=2 to t=8.5, relative temperatures in the presence and absence of the quad-layer increased at different water heating rates. The average water heating rates, measured after an initial 2-hour period with no significant temperature increase, were 0.93 ± 0.22°C/hr for the quad-layer of eggshells and 1.41 ± 0.28°C/hr for the control, indicating a 34.34% decrease for the eggshell layer (**Figure 7B**). Since the eggshell layer reduced the average water heating rate by over 30%, we concluded that the eggshell layer that covered half of the iced water surface slowed water heating. The ice in the control melted at 5 hours of measurement, and its relative in-water temperature reached ~8°C. On the other hand, in the presence of the quad-layer of eggshells, the relative in-water temperature reached ~8°C at 7 hours, delaying the water temperature rise or ice melting by ~40% in terms of time. At 8.5 hours, the quadruple eggshell layer cooled the water more than 5°C compared to the control with statistical significance ($p < 0.05$, **Figure 7B**), emphasizing the proper reflection of thermal radiation by the eggshell layer. Additionally, the relative air temperature with the eggshell layer at 7 hours was 13.90 ± 1.22°C, while the temperature of the control was more than 4°C greater, 18.27 ± 0.66°C, with statistical significance ($p < 0.05$, **Figure 7B**). In conclusion, the quad-layer of crushed eggshells demonstrated its effectiveness in slowing water heating, thereby delaying ice melting.

DISCUSSION

In this study, we aimed to develop environmentally friendly and sustainable solutions to mitigate the effects of climate change on melting Arctic Sea ice by repurposing everyday waste materials into effective thermal barriers. Specifically, we investigated whether the white inner surface of eggshells, when structured appropriately, reflects thermal radiation, delaying or preventing ice melting. Through the sets of experiments, we examined the relationships between parameters of materials, such as surface color and geometry, including thickness, and the reflection of thermal radiation to slow ice melting in water. The first objective of this research was to examine whether the surface color and thickness of floating materials affected water heating by reflecting thermal radiation. Based on our experimental results, color did not play

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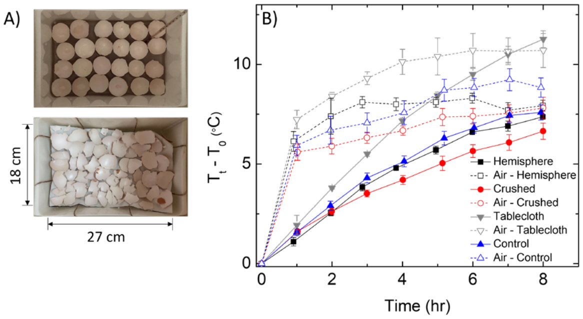

Figure 5. Impact of different eggshell geometries on reflection of thermal radiation. A) Images showing hemispheric eggshell layer (top panel) and crushed eggshell layer on tablecloth (bottom panel) on the water surface. **B)** Relative temperatures of water presented as a function of time ($T_t - T_0$) when applying the hemispheric eggshells, crushed eggshells on tablecloth, tablecloth alone, and control with water only. Data shown of mean ± SEM, n = 3, except for crushed eggshells with n = 6 and the control with n = 14.

a significant role in reflecting thermal radiation, while material thickness had a positive relationship with effectively slowing the rise of water temperatures, as shown by the difference in performance among Styrofoam, tablecloth, and the control setup with no materials on water. The second objective was to engineer eco-friendly eggshells as a thermal barrier. Based on the significance of material thickness, we constructed the multi-layered crushed eggshells. Consequently, we determined that the quad-layer of crushed eggshells on iced water not only substantially reduced water heating rates, thereby slowing ice melting, but also delayed the rise in air temperature in our testing environment.

While verifying the effects of material color and thickness on the reflection of thermal radiation, we encountered limitations in testing a wider range of thicknesses for tablecloths and Styrofoam. We were unable to source plastic tablecloths as thick as the Styrofoam we used and Styrofoam as thin as the plastic tablecloths we tested from commercially available sources. Additionally, further examining non-eco-friendly materials like plastic tablecloths and Styrofoam did not align with our goal of addressing environmental issues. Therefore, we applied our findings to eggshells, consistent with our objective of developing environmentally friendly and sustainable solutions.

When we arranged the crushed eggshells in a quad-layer formation, they slowed ice melting and the increase of water and air temperatures. Although it was obvious that increasing the number of eggshell layers enhanced the ability to slow ice melting, we only evaluated up to four layers to minimize the total weight of the eggshell structures. The density of crushed eggshells compared to their hemispheric counterparts exceeded the surface tension of water and sank, and thus, strings and tablecloths supported the crushed eggshell layers. Ceramic 3D printing can help overcome this sinking issue. Eggshells can be considered bioceramics, meaning that eggshell powders can be 3D printed through the process of sintering in any geometry that would maximize their ability to reflect thermal radiation and maintain an optimal balance between its density and surface tension, which will help practicalize the eggshell thermal barrier in the future (12, 13).

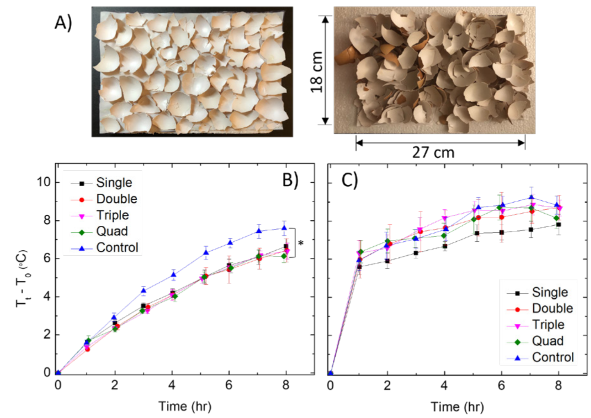

Figure 6. Impact of different numbers of crushed eggshell layers on reflection of thermal radiation. A) Examples of single- (left) and quad-layer (right) of crushed eggshells that nearly covered the whole water surface. **B)** Relative temperatures of water presented as a function of time ($T_t - T_0$) when applying the single, double, triple, and quadruple crushed eggshell layers, as well as no cover on the water surface. **C)** The relative air temperatures for each type of layer. Data shown of mean ± SEM, n = 6, except for the quad-layer with n = 9 and the control with n = 14; *$p < 0.05$ when comparing quad-layer of eggshells and the control. The other layers compared to the control showed no statistical significance in water or air.

Several unknown environmental factors need to be addressed during a future large-scale pilot test. Because the eggshell layer covered the water surface when evaluating the rate of ice melting and water heating, it is expected that numerous, gigantic-sized, floatable eggshell structures would be required to translate the obtained results from this research to the Arctic Ocean. As a result of utilizing the eggshell layer, the cooler water and air near the ice will help stabilize oceanic and atmospheric temperatures, mitigating further temperature increases. Although the deployed layers can achieve their main purpose, it would be necessary to conduct future field tests to understand their unexpected side effects on the Arctic Ocean. For instance, generated shades under the floated eggshell layers may or may not harm the marine ecosystem, such as phytoplankton, and require further investigation. Similarly, studying how the ecosystem adapts to icebergs, known for blocking sunlight and thermal radiation, could provide additional insights about the eggshells in the Arctic Ocean. However, at the same time, eggshells bring potential benefits to mitigate other issues caused by global warming, such as ocean acidification and the excess of CO_2 in the atmosphere. Ocean acidification is caused by high CO_2 absorption by the ocean (14). Eggshells, when decomposed, generate $CaCO_3$, which can react with the CO_2 from the ocean and raise the water pH, and potentially alleviate ocean acidification (15). Additionally, eggshell membranes are known to absorb CO_2 from the atmosphere (16). It is expected that the membranes of the deployed eggshell thermal barrier can remove carbon emissions, the primary culprit of raising temperature of the earth, from the atmosphere. Depending on the results of these positive effects, eggshell-based thermal barriers may even transit from a temporary solution to a permanent solution to mitigate global warming.

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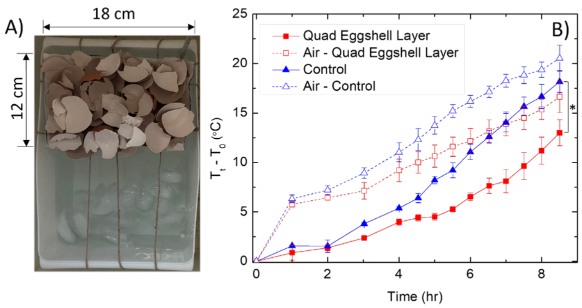

Figure 7. Impact of half-covered, quad-layer of crushed eggshells on reflection of thermal radiation and reduction of ice melting. A) The experimental set-up with the quad eggshell layer on iced water. Initial water temperatures were equilibrated for approximately 1 hour after adding ice. **B)** Relative water temperatures presented as a function of time ($T_t – T_0$) with the quad-layer of crushed eggshells and no cover on the iced water surface. Data shown of mean ± SEM, $n = 3$; $*p < 0.05$.

The key finding from our study highlights that the quad-layer of eggshells effectively slowed ice melting and maintained lower air temperatures than the control, demonstrating a notable ~4°C difference. This effect potentially mirrors the situation in the Arctic Ocean, where holding large masses of ice could help maintain cooler air temperatures and mitigate the impacts of climate change, including the reduction of natural disasters, such as intense wildfires. Additionally, the world produces approximately 86.7 million metric tons of eggs each year (17). Considering that an average egg has a surface area of about 86 cm^2 and weighs approximately 66 grams, our calculation indicates that up to ~2,800 km^2 of the quad-layer of eggshells can be prepared each year (18). Currently, eggshells, byproducts of eggs, are used for healthcare applications, but most are still considered waste (19-21). By repurposing and engineering eggshells, sustainable, biodegradable, eco-friendly, and feasible thermal barriers can be deployed in the Arctic Ocean. By reflecting thermal radiation, the engineered eggshells may eventually assist with cooling the atmosphere and reducing heat domes, thereby contributing to less frequent natural disasters. Consequently, the eggshell thermal barrier could offer significant benefits for human health and the environment.

MATERIALS AND METHODS

Homemade environmental chamber

To prepare the environmental chamber (**Figure 2**), six 0.49 m x 0.37 m Styrofoam pieces (Insulfoam, Puyallup, WA, U.S.A.) and three 0.37 m x 0.33 m Styrofoam pieces were prepared. Two 0.49 m x 0.37 m pieces and two 0.37 m x 0.33 m pieces were used to form the lateral sides of the box (**Figure 2A-i**). Two 0.49 m x 0.37 m pieces were stacked and glued (Gorilla Glue Co., Cincinnati, OH, U.S.A.) to build the bottom of the chamber. The third 0.37 m x 0.33 m piece divided the chamber in half, constructing two testing chambers and allowing two experiments to run at the same time. To adhere the Styrofoam pieces together, the glue was used, and then the sealant (Henkel Loctite, Rocky Hill, Connecticut) was applied to any adjacent Styrofoam pieces to prevent unexpected water leaking from the chamber during the experiment. To construct the lid of the environmental chamber, two 0.22 m x 0.28 m openings were cut out from the last two 0.49 m x 0.37 m Styrofoam pieces with a divider in between the openings, which aligned with the divider in the chamber (**Figures 2A-ii, 2B**). A cold rolled steel expanded sheet metal with a size of 0.30 m x 0.61 m and a mesh-like structure (The Hillman Group, Cincinnati, Ohio) was placed in between the prepared Styrofoam pieces with openings. The Styrofoam pieces were then glued together to keep the sheet metal in place (**Figures 2A-ii, 2B**). Two 50 W basking spot heat lamps (Omaykey, Shenzen Chaoren Network Technology Co., Ltd., Shenzen, China) with a sun dome (Fluker's Cricket Farm, St. Allen, Louisiana), the light and thermal source (**Figure 2A-iii**) of each testing chamber, were placed on the sheet metal (**Figures 2A-ii, 2B**). The lamps were 0.3 m away from the water surface.

In each testing chamber, a storage container (Container Store, Coppell, Texas) with 3.0 L of water or 2.0 L of water with ~1 kg of ice was located (**Figure 2A-iv**). Moreover, 35 g of salt was added per liter of water to simulate the ocean (22). Furthermore, to monitor the temperature, two thermometers (Seoh, Houston, Texas) were prepared in each testing chamber. One thermometer measured the air temperature and was attached to the wall of each testing chamber, while the other one gauged the in-water temperature (**Figures 2A-v, 2A-vi**). To avoid any unexpected incidents such as leaking or flooding of water outside the environmental chamber, the chamber was placed in a tote box (**Figure 2A-vii**; Sterilite, Townsend, Massachusetts).

A 50 W heat lightbulb was chosen as a thermal radiation source because it maintained air temperatures below 40°C, which is the maximum, or extreme, temperature ever recorded during Arctic summers (23).

Materials preparation

Polyethylene-based plastic tablecloth (Brother Sister Design Studio, Oklahoma City, Oklahoma) and Styrofoam were painted using appliance epoxy spray paints (Rust-oleum, Vernon Hills, Illinois) to prepare white and black versions for each material. To prepare diverse geometries made of eggshells, a layer with hemisphere-shaped eggshells was assembled by cutting cleaned eggshells in half, which adhered side-by-side using a hot glue gun (**Figure 2A-viii**). Moreover, an eggshell layer was constructed by gluing crushed eggshells in a single layer on the tablecloth, using adhesive spray (3M, Saint Paul, Minnesota). Eggshell multi-layers were constructed by gluing more crushed eggshells on top of the prepared single-layer of eggshells on the tablecloth.

Data collection procedure

To understand the effect of surface color and thickness of materials on water heating, prepared materials were placed on water inside the container, located in one of the testing chambers of the environmental chamber (**Figure 2A-iv**). The control, without any material on the surface, was located in the other testing chamber.

The temperature data were recorded to evaluate prepared materials as thermal barriers. Initial water and air temperatures in each testing chamber were measured (t=0), and then the heat lamps were turned on. The temperature changes in water and air within the chamber were recorded every hour up to around 8 hours (t=1, 2, 3, ..., 8 hrs.), where air and in-

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water temperatures approached a plateau. Despite efforts to measure temperatures precisely, manual measurements introduced variability in timing, particularly around the 8-hour mark (**Figures 3-6**). Nevertheless, the average temperature and SEM indicated that temperatures had already plateaued by the time they were measured in the 7:30 to 8:20-hour range, resulting in a small SEM relative to the average temperature. Additionally, to enhance the data accuracy when measuring temperatures, in-water and air temperatures between the two testing chambers were equilibrated to < 2°C difference before the initial measurement (t=0).

While testing materials were placed on 3 L of water when measuring water heating without ice, to evaluate the effect of the eggshell layers on delaying ice melting, 2 L of water was cooled in the refrigerator overnight, and ~1 kg of ice was added to the water in the containers (**Figure 2A-iv**). The environmental chamber was then closed for a minimum of one hour to equilibrate in-water and air temperatures. Data was collected for 8.5 hours. When all ice melted before 8.5 hours, the time when it completely melted was recorded, and the temperature and time continued to be carefully recorded until 8.5 hours was reached (**Figure 7**).

Initial water and air temperatures for Figures 3-7

The initial water temperatures were 24.73 ± 0.71ºC for black tablecloth, 24.83 ± 0.44ºC for white tablecloth, 24.72 ± 0.58ºC for black Styrofoam, 24.98 ± 0.43ºC for white Styrofoam, 22.30 ± 0.20ºC for hemispheric eggshells, 23.30 ± 1.34ºC for crushed eggshells, 19.50 ± 0.56ºC for tablecloth, 23.30 ± 1.34ºC for single-layer of crushed eggshells, 23.10 ± 1.09ºC for double-layer of crushed eggshells, 22.65 ± 0.59ºC for triple-layer of crushed eggshells, 22.91 ± 0.87ºC for quad-layer of crushed eggshells, and 21.93 ± 0.50ºC for the control with only water (**Figures 3B, 4B, 5B, 6B**). The initial ice water temperatures were 2.07 ± 0.41ºC for the half-covered, quad-layer of crushed eggshells and 0.80 ± 0.10ºC for the control with only ice and water (**Figure 7B**).

The initial air temperatures were 25.73 ± 0.57ºC for black tablecloth, 25.77 ± 0.23ºC for white tablecloth, 24.72 ± 0.58ºC for black Styrofoam, 24.98 ± 0.43ºC for white Styrofoam, 23.83 ± 0.03ºC for hemispheric eggshells, 23.95 ± 1.07ºC for crushed eggshells, 20.73 ± 0.48ºC for tablecloth, 23.95 ± 1.07ºC for single-layer of crushed eggshells, 24.10 ± 1.12ºC for double-layer of crushed eggshells, 23.90 ± 0.74ºC for triple-layer of crushed eggshells, 23.83 ± 0.75ºC for quad-layer of crushed eggshells, and 22.63 ± 0.53ºC for the control with only water (**Figures 3B, 4B, 5B, 6C**). The initial air temperatures of the ice water were 8.53 ± 0.30ºC for the half-covered, quad-layer of crushed eggshells and 7.97 ± 0.03ºC for the control with only ice and water (**Figure 7B**).

Data analysis

All experiments were performed with three or more replicates, and analyses were run as independent replicates, measured on different dates. All quantitative data were analyzed using descriptive statistics (mean ± SEM) of the relative temperature. The relative temperature was calculated by comparing recorded temperatures in each interval relative to the initial temperature when time (t) was at 0 hour ($T_{t=1, 2, 3…,8} – T_{t=0}$). All determined relative temperatures were graphed as a function of time, using the Origin graph software (OriginLab Corp., Massachusetts). The water heating rates were calculated by averaging the hourly temperature changes observed after the initial 2-hour period with no significant temperature increase, $[\Sigma^{t=n}_{t=2}(T_t – T_{t-1})] / (n - 2)$. To understand the statistical significance of obtained data, differences among experimental groups were evaluated at each time point using *p*-values derived from student T-tests.

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