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Impact Of Various Adsorbent Materials On The Zeer Pot's Rate Of Evaporative Cooling

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Abstract: *The magnitude of post-harvest food losses caused by ineffective storage mechanisms andthe high energy requirements of electrical refrigeration deviceshave drawn attention towards the zeer pot. Zeer pots, or clay pot coolers, harness the principle of evaporative cooling to result in lowered internal temperatures required for the preservation of fruits and vegetablesthrough a zero-carbonmethod. Thedevice does not require electricity, making it useful for off-grid communities in hot and dry regions. This paper explores the impact of adsorbent material on the rate of evaporative cooling of the zeer pot. Through setups involving sand, only water, sponge, hydrophobic sand, soil and fenugreek plants, the impact of type of material, including its hydrophobicity or hydrophilicity, on the rates of capillary action and cooling over a 24-hour periodare investigated. Findings indicate fluctuations in cooling rates are time-dependent as the storage chamber'stransition and steady state temperatures occur during similar timeintervals for all setups. However, material choices impact average cooling magnitude. Sand was the most effective adsorbent mediumand reached sub-wet-bulb temperatures, with hydrophilic materials outperforming hydrophobic counterparts.*

Keywords: *evaporative cooling, zeer pots, adsorbent materials, hydrophobicity, hydrophilicity*

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I. INTRODUCTION

The United Nations estimates that 821 million people around the world suffered from hunger in 2018,an issue aggravated by food spoilage and losses between producers and consumers. Large proportions of this loss, nearly 40% of the total loss in developing countries [1], occurs in the post-harvest stage with prevailing food storage and preservation technologies relying on electricitythat is often inaccessible, erratic or unaffordable for rural communities. The lack of clean, inexpensive and effective post-harvest storage solutions culminates in income loss and food insecurity. These off-grid communities find themselves forced to 'rush sell' their products, despite the financial setbacks that flooding the market with produce can pose. Those unable to sell their produce face spoilage. Beyond the rural setting, numerous urban slum-dwellers have limited access to electricity required for refrigeration, impeding the UN Sustainable Development Goal of achieving zero world hunger by 2030. The malnourishment phenomenonis severe in developing countries where poverty culminates in diminished nutrition.

Most modern-day refrigerators use refrigerants that pose threats to the environment including accelerated rates of depletion of the ozone layer and enhanced greenhouse effect. Therefore, there is a need for an efficient, inexpensive, scalable, non-polluting cooling and storage application that does not require electricity.

Zeer pots can prove effective in increasing shelf lives of produce for marginal farmers and market vendors. While evidence of evaporative cooling traces back to ancient civilizations (the Indus Valley and Egyptian,) the invention of electrical refrigerators resulted in diminishing use of clay pots for food storage. Zeer pots however do not require electricity, making them viable solutions for areas with no electricity access or where supply is erratic and prices high.

II. BACKGROUND INFORMATION

A. Basic Construction and Cooling

The zeer pot constitutes a clay pot placed within a larger pot; the gap between them is filled with an adsorbent material (typically sand) which is frequently replenished with water needed for evaporative cooling (Section *IIB*.) Pots are modelled from clay since clay is porous and has low thermal conductivity, facilitating the movement and evaporation of water. The food is placed within the smaller pot or 'storage chamber' and covered with an airtight lid or damp cloth. This evaporation causes the relative humidity of the internal pot to increase while the temperature within the pot decreases in comparison to ambient conditions.

The lower temperature slows microbial, particularly bacterial, growth which can hasten food spoilage. Additionally, the high humidity increases the shelf life of produce as it reduces the rate of water loss and respiration. Typically, fruits and vegetables contain between 65-95% water by mass.[2] Once harvested this water content begins to decline, eventually resulting in deterioration. Therefore, high storage humidity prevents the loss of water byminimizing the humidity gradient. The level of cooling facilitated by a zeer pot makes it appropriate for preserving fruits and vegetables rather than meats and dairy.

B. Evaporative Cooling

In zeer pots, the evaporation of water results in the cooling effect. This is particularly effective as water has the largest latent heat of vaporization of all liquids – it requires 2,260kJ of energy per kg to vaporize.[3]Due to forces of cohesion and adhesion, water travels via capillary action through the pores of the clay pot to its outer surface from where it evaporates. As it evaporates, it gains latent heat from the pot, resulting in a temperature drop.

It follows that the rate of evaporation of water is inversely proportional to surrounding humidity. Very dry air can absorb high amounts of moisture unlike nearly saturated air. When the ambient humidity is high, the humidity gradient between the pot and the surroundings is smaller. Consequently, the driving force is less significant and hence the rate of evaporation decreases. For evaporation to occur, the molecules of the liquid must have sufficient energy to overcome the intermolecular hydrogenbonding in the liquid phase. Since temperature is directly proportional to kinetic energy, as temperature increases, more particles have sufficient energy to escape, increasing the rate of evaporation. This evaporative cooling is caused by convective and radiative heat transfer.

Should there be no external influences the rate of evaporative cooling decreases over time as the evaporation of water results in the increase of surrounding relative humidity. However, a high flow velocity air causes the zeer pot to be continually surrounded by dry air, resulting in a higher rate of evaporation.

The adsorbent material facilitates evaporative cooling. Water travels through the material's pores to the outer clay pot. It is then exposed to the surroundings and evaporative cooling occurs. In fact, wet sand has a higher thermal conductivity than water itself – it conducts heat better than water, allowing for a faster temperature decrease within the inner pot. The lower thermal conductivity of dry sand allows it to function as an insulator, keeping food cool even when rates of evaporative cooling have dropped due to ambient conditions or extensive evaporation.

C. Hydrophobicity and Hydrophilicity

Water is a polar molecule because of its bent shape and due to the fact that oxygen is more electronegative than hydrogen (According to the Pauling scale, oxygen's electronegativity is 3.44 while hydrogen's is 2.20.) Therefore, while the molecule has no overall charge, the oxygen and hydrogen atoms develop partial negative and positive charges respectively as oxygen attracts the electrons in the covalent bond more strongly. The polarity causes water molecules to attract each other, resulting in the formation of hydrogen bonding between the partially positive hydrogen atom of one molecule and the oxygen atom of another molecule.

When water is more strongly attracted to the material than itself, the material is "water-loving" or hydrophilic. Hydrophilic materials form ionic or hydrogen bonds with the water molecule; these bonds are stronger than the hydrogen bonds between water molecules. When water is in contact with such a material it spreads across it, maximizing contact. The contact angle is less than 90°.

A material is considered hydrophobic when water is more strongly attracted to itself than it is to the material. Hydrophobic materials typically constitute non-polar molecules which repel water, resulting in the formation of water droplets. The contact angle between the material and the water molecule is greater than 90°.[4]

D. Pschrometric Properties and the psychrometric chart

The following psychrometric properties facilitate a parametric analysis.

1) Relative Humidity

Relative humidity is the amount of water vapour present in air expressed as a % of the amount needed for saturation at the same temperature. It may also be expressed as the ratio of the vapor pressure of moisture in the sample to the saturation vapor pressure at a fixed temperature. As air temperature increases, air can hold more molecules of water and hence relative humidity decreases.Relative humidity is temperature dependent – a high relative humidity in the cold typically indicates a relatively low moisture composition by mass. While the relative humidity may be much higher, most naturally-occurring humid air has a maximum of 3-3.5% water vapour by mass. [5]

2) Dry Bulb Temperature

Dry bulb temperature is the temperature directly measured by a thermometer sheltered from direct solar irradiance. Air is considered to be saturated when the dry bulb temperature is equal to the dew point temperature.

3) Wet Bulb Temperature (Tw)

The wet bulb temperature is the minimum temperature to which air at a particular surrounding temperature and humidity level can be cooled by the evaporation of water into the surroundings at fixed pressure. It can be found precisely using the psychrometric chart but modelsare used for its approximation. Wet bulb temperature is a theoretical thermodynamic limitation to how 'cold' the pot can get.

4) Minimum Temperature of Approach

The minimum temperature of approach refers to the minimum temperature difference between the pot and its surroundings for which heat transfer can occur. While theoretically this can occur for any temperature difference greater than 0°C, the transfer is often not substantial enough to be detected.[6]

Correlating these properties, Willis Carrier developed the psychrometric chart. Developed from the pressure-temperature diagram for water in its three phases, the psychrometric chart includes dew point, dry-bulb, wet-bulb temperature, specific humidity and relative humidity.

III. MATERIALS AND METHODOLOGY

The experimentinvolved five adsorbent materials: no material (only tap water), sand from the Kaveri River, soil and fenugreek plants, hydrophobic sand and sponge.

The set-up involved a large pot with a diameter of 10 inches and a smaller pot with diameter 6 inches. The pots were washed with water and the base sealed with hardened epoxy to prevent water leakage. The pots were dried and polystyrene lids of the same diameter as the small pot were created with two perforations. The larger pot was filled with adsorbent material until half way full and the smaller pot placed within such that the rims of both pots aligned. The gap between the surfaces of the pots were filled with the material. The humidity and temperature logger's (Elitech Log) sensors were inserted in the sealed storage chamber. Water was poured between the pots until the material neared saturation and data was logged at 1-minute intervals for 1,448 minutes(24 hours.) The water level was checked at 5-hour intervals and replenished as necessary.

Fig. 1. Basic Zeer Pot Setup

In the setup with fenugreek, plantlets were grown separately and transferred to the pot before adding water. To create hydrophobic sand, sand was sprayed with water-repellant spray and dried. Its hydrophobic properties were confirmed prior to experimenting.

Fig. 2. Top view of setup with sponge and data logger

IV. DATA, ANALYSIS AND DISCUSSION

E. Qualitative Data

The time taken for the water level to fall by around 2 centimeters, change in color of pots and the perceived change in surface moisture by touch were determined topre-indicate the impact of adsorbent material. In Setups A (only water) and E (hydrophobic sand), it was found that the outer surfaces of both pots were soaked and the colors darkened. While this would suggest adequate rates of capillary action, no conclusion can be drawn considering the nature of the setups wherein water was in direct contact with the pots. In Setups B (sand) and C (sponge), the color of the external pots changed to patchy brown after an hour, highlighting that capillary action was not instantaneous. Water levels diminished every 5 hours in Setup B and every 6 hours for sponge, indicating greater rates of evaporative cooling for sand. For Setup D (fenugreek) no water in the liquid phase collected in the storage chamberindicating that lesser evaporation had occurred.

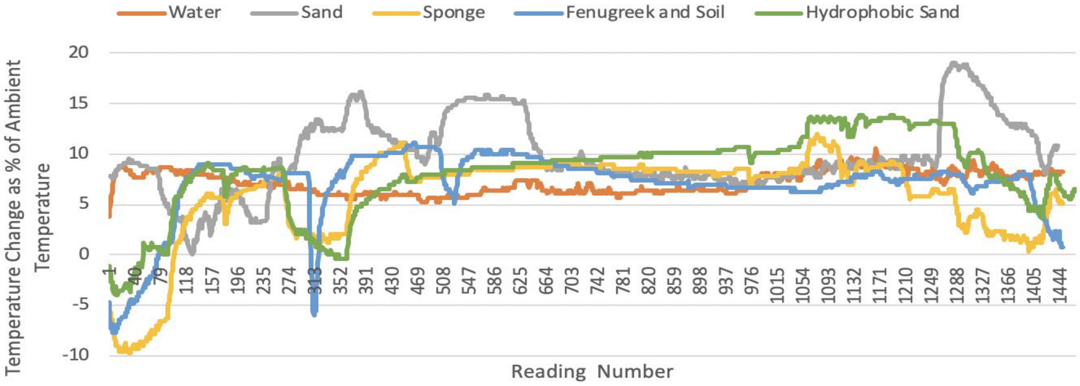
F. Quantitative Data

Considering that ambient temperature and relative humidity fluctuated within and between setups, wet bulb temperature was calculated to indicate the zeer pots' cooling efficiency.To estimate wet bulb temperature from ambient relative humidity and temperature the Stull formula was used: $T_w = T_a \times \arctan(0.151977 \cdot (RH_a + 8.313659)^{\frac{1}{2}} + \arctan(T_a + RH_a) - \arctan(RH_a - 1.676331) + 0.00391838 \cdot (RH_a)^{\frac{3}{2}} \times \arctan(0.023101 \times RH_a) - 4.686035,$where T_w is wet-bulb temperature in °C, T_a is ambient temperature in °Cand $RH_a$is ambient relative humidity.Wet bulb effectiveness, $\eta,$ of the system was calculated as: $\eta = \frac{T_a - T_i}{T_a - T_w}$, where T_i= internal temperature in °C.

G. Data and Graphical Analysis

Graph 3.1 depicts differences in the extent of cooling of all setupswith reference to time and in comparison with each other. Sand produces the greatest relative change in temperature of the storage chamber,with a maximum drop equivalent to 19.084% of ambient temperature occurring at Reading 1283. In contrast at this point, other set-ups have temperature drops ranging from 2.632% to 9.663% of the ambient temperature, revealing that the temperature drop with sand is more than twice that of the next most effective material. This is reinforced by sand consistently having the highest cooling efficiency – for example, it crosses 15% between Readings 364 and 380readings and then between 526 and 616. The temperature change as a % of ambient temperature does not cross 15% for any other setups. A series of anomalous data points are detected for Setup E(fenugreek and soil) between readings 302 and 355, with the internal temperature taking a higher value than the ambient. This is likely to have been caused by changes in air conditioner and dehumidifier cooling rather than by changes in rates of capillary action or evaporation. Additionally, the % change remains relatively constant for water, remaining between 5-10% throughout after an initial lag. The relatively constant measure of this magnitude is likely to be caused by the constant contact between water and the pots' surfaces. Setup E has the lowest change due to problems arising with the replenishment of water. More importantly, based on Graph 3.1, it is apparent that the extent of cooling is impacted more significantly by time since evaporative cooling initiated than it is by the nature of the adsorbent material between pots. The temperature change as % of ambient temperature for all setups peaks by the 450th reading, after which it remains in the steady state until the 1048th reading, reaching a local maxima and then reducing once again. While other setups show sudden spikes, hydrophobic sand shows a sustained increased

Graph 3.1 Temperature Difference between Surroundings and Storage Chamber



which can be attributed to the constant contact between water and the pot which occurs only in setups including hydrophobic sand and no adsorbent material.

Graph 3.2 depicts changes in wet-bulb effectiveness, defined in Section IVB, with time. It is clear that for water and sand as adsorbent materials, the cooling efficiency increases to values above 1 (=100%.)As wet-bulb temperature is the lowest temperature that can be attained by evaporativecooling at particular ambient conditions, these readings may seem anomalous. However, this is impacted by both errors of the logger and the model estimating T_{wb} from T_a and RH_a as depicted in Table 1. The Stull formula is prone to errors as it is a best-fit estimation of the Mollier Diagram.

Graph 3.2 Change in Wet-BulbEffectiveness with Time

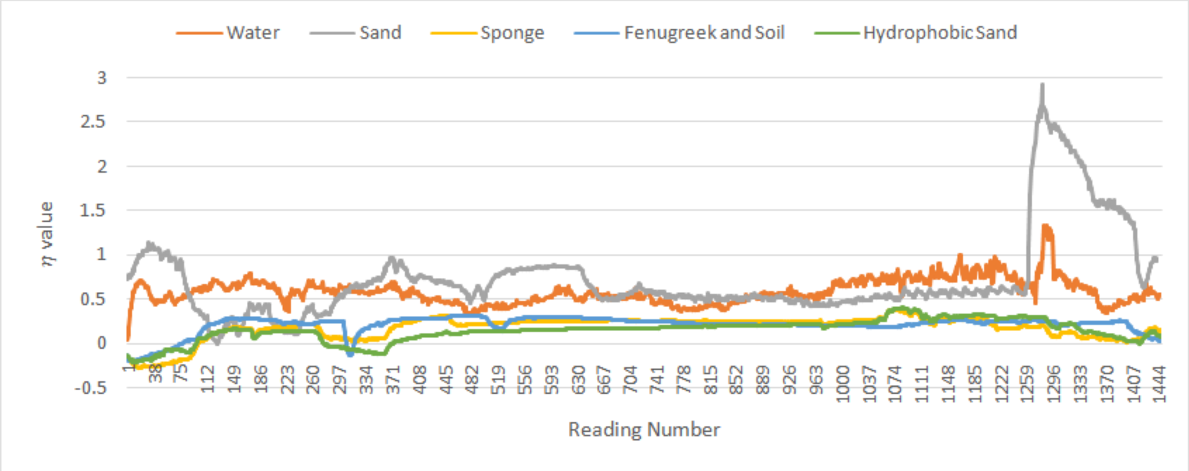


TABLE I. EXPERIMENTAL UNCERTAINTIES

Measurement	T_a Logger	RH Logger	Stull Formula*
Uncertainty Range	±0.5℃	±3% RH	−1to 0.65℃

*This error range is only valid for measurements between -20 to 50℃ and 5-90% RH (apt for the experiment.)

Based on this the percentage uncertainty in the η value for Point 1280 for Setup C (maximum η value obtained) is found to be approximately10.0175%. Hence, there is a significant error margin considering the nature of the data and models used. More importantly, the sub wet-bulb temperatures (or wet-bulb effectiveness greater than unity), may be attributed to the construction of the zeer pot. Typically, the use of evaporative cooling is limited as the minimum storage temperature attainable is equivalent to the wet-bulb temperature. However, this result points towards the applicability of zeer pots on a large scale due to the level of cooling they can facilitate. Additionally, since the experiment was conducted towards the upper limit of relative humidity, often reaching nearly 85% relative humidity, the Stull Formula may have been an inadequate representation of wet-bulb temperature. From Graph 3.2, it is evident that as temperature on average, normal sand outperformed hydrophobic sand. Dry sand consistently displayed a η value greater than its hydrophobic counterpart.

A one-way ANOVA (analysis of variance) test was conducted to determine the results' statistical significancefrom which MSE =0.0580426. $\left(Mean\ Square\ Error = \frac{SSE}{n-k} = \frac{419.53}{7228}\right)$ The low value of the mean square error suggests that the results are significant. From the ANOVA test it was also found that p-value $<a$, indicating that the null-hypothesis, or the hypothesis that material has no impact on extent of evaporative cooling, can be rejected.

TABLE II. AVERAGE COOLING EFFICIENCY

Set-up	*A*	*B*	*C*	*D*	*E*
Mean η value	0.5858	0.7241	0.1758	0.2101	0.1441

It is therefore evident that the cooling efficiency is highest for sand as an adsorbent material, followed by only water, fenugreek and soil, sponge and finally hydrophobic sand. While Setups C displayed average cooling efficiencies within the same range (0.14 - 0.21), sand and only water were significantly more effective, with sand displaying a cooling efficiency that was more than five times that of hydrophobic sand. This could be because of the porosity of sand which allowed for percolation of water throughout the pot, unlike in the case of hydrophobic sand.

To confirm the efficacy of a zeer pot's evaporative cooling phenomenon,an unripe banana was placed in a zeer pot with another being placed in a simple pot with no water supply. It was found that while the banana in the simple pot ripened in 3 days, the other set-up required 6, validating the applications of the result.

V. CONCLUSION

It is evident from the parametric analysis that time is the most important factor indeterminingchanges in rate of cooling while type of adsorbent material influences magnitude of evaporative cooling. For the setup with sand (hydrophilic) the magnitude of evaporative cooling was greatest in comparison with other materials. Despite the preliminary assessment that the growth of fenugreek would result in greater evapotranspiration and consequently a larger temperature gradient, soil liquefication prevented the addition and subsequent percolation of water, resulting in a low internal relative humidity. The role of the humidity gradient, which provides the driving force for evaporation, has been reinforced by the data collected.

Based on the type of fruit or vegetable being preserved, the ideal material differs; for example, grapes can tolerate temperature fluctuation, making sand a suitable material for storage as it provides greatest cooling effect. For asparagus, appearance deteriorates, hardness rises and ascorbic acid content decreases astemperatures fluctuate. Thus, water or hydrophobic sand is suitable for its preservation albeit the open storage of water in especially sunny areas may result in rapid water loss. In particularly arid areas, this setup requires abundant water which may not be attainable. In conclusion, extent of cooling is largely time-dependent; however, based on specific contexts, micro-climates and preservation requirements, different adsorbent materials should be used.

VI. EVALUATION

This investigation did not entail providing the same volume of water to each zeer pot which may have limited the extent of evaporative cooling for setups where water diminished rapidly. Therefore, each pot should have been provided by the same initial volume of water; however, it is essential to consider the impact this could have on the liquefaction of the adsorbent material and the notion that in Setup 2 with no adsorbent material, the water would not reach the upper surface. The zeer pots were placed on the ground, inhibiting evaporation from the bottom surface. The experiment could be extended by elevating the pots using a stand such that the bottom surface of the pot is exposed to airflow as well. Accounting for the difficulty in maintaining constant relative humidity, this experiment made use of a dehumidifier. However, this was insufficient in maintaining a constant relative humidity, instead providing a very large range between 50 and 80%. The ambient temperature varied significantly as well, dropping suddenly and impacting wet-bulb temperatures. Thus, the experiment could have been conducted within a climate chamber.

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