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Reducing Evaporation from Arid Soil in Jordan Through Absorbent Materials: Volcanic Tuff, Wood Ash, and Date Pit Ash

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ABSTRACT

Irrigation water represents the primary water usage in arid regions worldwide, reaching up to 70% in some countries. However, more than 90% of that water is lost by evaporation in arid regions. This study aims to reduce the soil evaporation rate in Jordan, a water-scarce country, using water-absorbent materials that are both affordable and environmentally friendly. Our research used three absorbent materials: volcanic tuff, wood ash, and date pit ash. These materials were characterized by different analytical methods to investigate their chemical composition, mineral content, specific surface area, and microstructural morphologies. Three different soil, absorbent materials, and water mixtures were prepared in specific ratios. The evaporation rates for the mixtures were estimated in an open area using a time-domain reflectometry sensor during the winter of 2022. The soil temperature, relative humidity, and wind speed conditions were recorded. It was found that these materials have a significant efficiency in reducing the evaporation rate related to their internal structure. The study suggests utilizing biomass ash to alter the internal structure of soil aggregates, thereby improving water retention and lowering evaporation rates. This action would diminish the need for irrigation, consequently bolstering sustainable water resources.

1. INTRODUCTION

The primary challenges facing people and governments in arid and semiarid regions are decreasing crop production, agricultural land deterioration, and desertification. Soil and water management are essential to success. Reducing water consumption in irrigation and enhancing soil conditions using water-absorbent materials that reduce water evaporation is mainly required for sustainability. It is essential for conserving water, especially in arid regions with limited water resources. Evaporation increases as the humidity drops, the air warms, or the wind strengthens [1]. Several methods are traditionally used in order to reduce evaporation from the soil, such as organic mulch [2, 3], cover crops [4, 5], reduced tillage [6, 7], drip irrigation [8, 9], and evaporation suppressants [10, 11]. Implementing a combination of these methods based on local constraints can reduce soil evaporation and water consumption for irrigation. However, soil-reducing evaporation methods pose specific challenges that require consideration of several factors, such as financial cost, suitability for soil types and climatic zones, the education level of the farmers, and the environmental impact of the method used on the soil. However, that process requires developing an effective solution to avoid those issues by utilizing low-cost, environmentally friendly absorbent materials which can be applied easily, regardless.

Jordan is a dry region with few water resources. The mean annual water supply is below 500 m^3 [12]. Water losses from evaporation were reported to be 91.8% of the total annual rainfall in 2014–2015 [13]. However, the two significant challenges for agriculture are water scarcity and the high evaporation rate of its arid soil. Hence, sustainable management of soil and water is inevitable. Accordingly, the objectives of this research are: Characterize the collected materials to assess their water-holding capability, perform the evaporation rate test for arid soil samples by adding the characterized materials under the climatic conditions and assess the potential usage of three water-absorbent materials to reduce soil evaporation rates.

Collecting samples of low-cost absorbent materials: 1) Volcanic tuff is a fragmented volcanic material characterized by different grain sizes and textures, high porosity, and low density [14]. In Jordan, volcanic tuff covers a large, arid area called the Black Desert. Volcanic tuffs show good adsorption and ion exchange properties [15]. Volcanic tuff is extensively applied as a soil amendment material for improving the absorption and preservation of water [16-19]. Rădulescu [15] found that adding the zeolitic volcanic tuff increased the soil humidity. Al-Busaidi et al. [20] reported that zeolitic tuff enhances soil's water-holding capacity. Owais et al. [21] indicated that water consumption decreased significantly, about 46.5–67.8%, by using volcanic tuff; 2) Biomass ash materials include wood ash and date pit ash. Wood ash is the residue remaining after the incineration of wood for energy production. Date pit ash is produced by burning dates' pits (seeds). Date pits are the complex, inner parts of dates, typically removed before consuming the fruit. Ash materials are porous, have a low density, and have a small particle size. Burning wood and consuming dates result in much waste being disposed of in landfills. Reusing it helps to reduce waste, which is beneficial to the environment. Numerous studies have demonstrated that wood ash applications as a soil amendment improve tree growth [22-25]. Limited studies investigate the utility of biomass ash in reducing soil water evaporation. Yang et al. [26] added biomass ash to the soil and found it can effectively reduce evaporation. Li et al. [27] studied the effects of different biomass ash contents on soil evaporation and cracking. The results show increased biomass ash content increases evaporation time with a decreasing crack ratio. Huang et al. [28] found that the biomass ash improved the soil structure, soil consistency, and water-holding capacity.

2. MATERIALS and METHODS

2.1 Materials and characterization

For this study, an arid soil sample was collected at around 20 cm from the ground surface on the Hashemite University campus, approximately 25 km northeast of Amman, Jordan. According to the United States Department of Agriculture's (USDA) Soil Taxonomy, the type of soil is aridisols. A low organic matter content and desert pavement characterize it. The soil sample was oven-dried. Three different absorbent materials were used as additives to examine their efficiency in evaporation reduction. Wood ash was obtained from a home wood stove after burning forest tree trunks and sieved to a grain size of approximately 425 μm. Date pits were collected from a local date manufacturer, crushed, milled via an electric grinder, sieved to a grain size of around 425 μm, and thermally treated in an open furnace at around 560-600℃. Volcanic tuff aggregates were obtained from Tall Hassan (latitude: 31°57'19.08" and longitude: 36°54'28.94"), about 125 kilometres northeast of Amman. The volcanic tuff aggregates were sieved, and a grain size of 1.18 mm was used. The chemical composition of the materials was measured by X-ray fluorescence (XRF) using an S8 Tiger and Bruker AXS with a loss on ignition (LOI) measured at 1000℃. The mineral composition was determined by an X-ray diffractometer (XRD-7000, Shimadzu) using Cu Kα radiation in the 5–60° range with a scan rate of 2°/min. Microtrac Belsorp Max II determined the pore size analysis using liquid nitrogen at 77 K. The specific surface area was performed by BET (Brunauer-Emmett-Teller) at a range of 0.01 to 0.35. The microstructural analysis was performed using scanning electron microscopy (SEM, Quanta 600, FEI).

2.2 Evaporation rate test

For the evaporation rate test, three sets of 300 g soil were mixed with 100 g of three absorbent materials (wood ash, date pit ash, and volcanic tuff) in a 500 ml beaker. 100 ml of water was added to the mixture gradually in a controlled manner by using a watering can. In order to measure the actual evaporation rate, the prepared mixtures were put in a garden where all the natural evaporation conditions were running. The test was performed during winter 2022, from December 17 to December 30, when no rainfall might affect the evaporation measurement. The evaporation rate of the prepared soil mixtures was measured precisely using a TDR (Time-domain reflectometry) sensor. The soil temperature, relative humidity, and wind speed conditions were recorded.

3. RESULTS and DISCUSSION

3.1 Materials characteristics

The results of chemical analysis for absorbent materials using an XRF analyzer are shown in Table 1. The results indicated that wood ash consists of many major and minor elements that trees need for growth. Calcium is the most abundant element in wood ash (36.4%). Ash is also a good source of potassium (16.6%), along with some amounts of silicon (4.87%), magnesium (3.59%), and aluminum (1.68%). The analysis shows that date pit ash has a high percentage composition of silicon, potassium, and phosphorus (19.50%, 18.5%, and 18.2%, respectively). The results reveal a presence of 10.30% calcium, 9.05% magnesium, 6.39% aluminum, and 5.77% iron. The chemical composition of volcanic tuff shows that the sample is primarily rich in silicon (42.50%), in addition to aluminum (15.60%), iron (13.50%), calcium (10.50%), and magnesium (6.06%) oxides.

Figure 1 presents the diffractogram of wood ash using XRD analysis. The findings indicated the presence of calcite ($CaCO_3$) as a dominant mineral, along with lime (CaO), fairchildite ($K_2Ca(CO_3)_2$), and a minor amount of quartz (SiO_2). The diffractogram of date pit ash in Figure 2 shows broad peaks, indicating that most matter is amorphous. The mineralogical composition of volcanic tuff indicates that the detected zeolite phases, plagioclase $(Na,Ca)(Si,Al)_4O_8$, and pyroxene $(NaCa)(Mg,Fe,Al)(Al,Si)_2O_6$), with the addition of olivine ($(Mg,Fe)_2SiO_4$), are significant minerals (Figure 3).

The adsorption and desorption curves of absorbent materials are shown in Figure 4(a), (b), and (c). The surface area of wood ash, date pit ash, and volcanic tuff is determined using BET analysis. As the obtained isotherms show, according to the IUPAC (International Union of Pure and Applied Chemistry) classification, the type IV isotherm with the hysteresis loop can be detected. The hysteresis loops of the adsorbent suggest that the H4 form demonstrates narrow, slit-like pores. As measured by the BET test method, the surface areas of wood ash, date pit ash, and volcanic tuff are about 42.0, 23.1, and 13.5 m^2/g, respectively. Consequently, the uptake capacity of wood ash is higher than that of date pit ash and volcanic tuff.

The morphological aspects of the absorbent materials particles are obtained through SEM, illustrated in Figures 5, 6, and 7. It was observed that the wood ash was composed mainly of a heterogeneous structure and an irregular morphology in terms of the size and shape of particles (Figure 5). The SEM micrograph of date pit ash is shown in Figure 6. It is observed that the surface of particles is porous and non-crystalline due to thermal treatment and is agglomerated, which results in the formation of bigger particles. Additionally, cracks are present due to the loss of volatiles and organic components during burning. The SEM micrograph of volcanic tuff is shown in Figure 7. The micrograph of volcanic tuff shows particles with mostly prismatic and irregular shapes. Wood ash has the smallest grain size, more regular shapes, and more micropores than date pit ash and volcanic tuff, showing a larger grain size and less porosity. Therefore, wood ash's surface area and porosity might be high, which is beneficial for water retention.

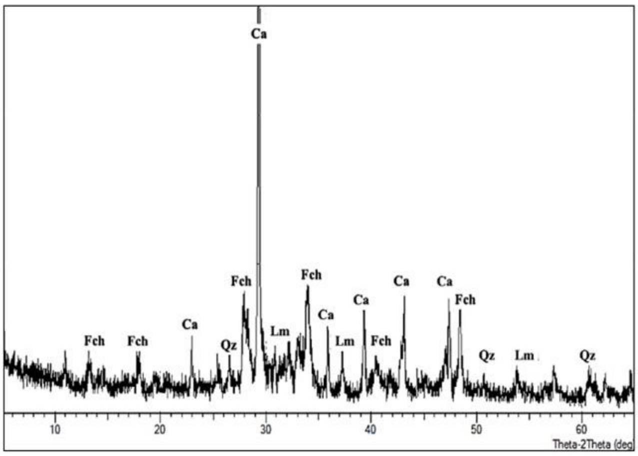

Figure 1. XRD spectrum of wood ash
Ca: calcite, Lm: lime, Fch: fairchildite, and Qz: quartz

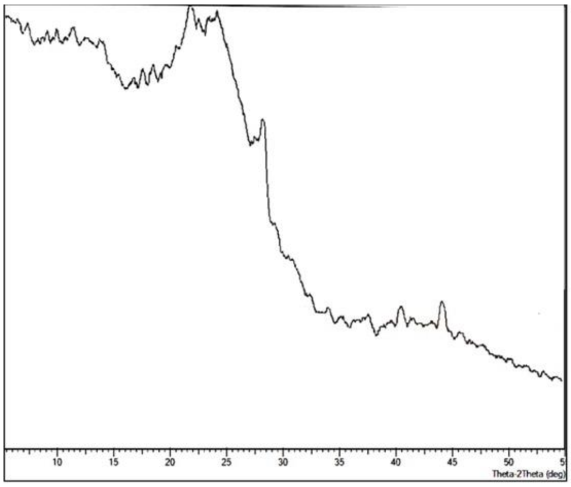

Figure 2. XRD spectrum of date pit ash

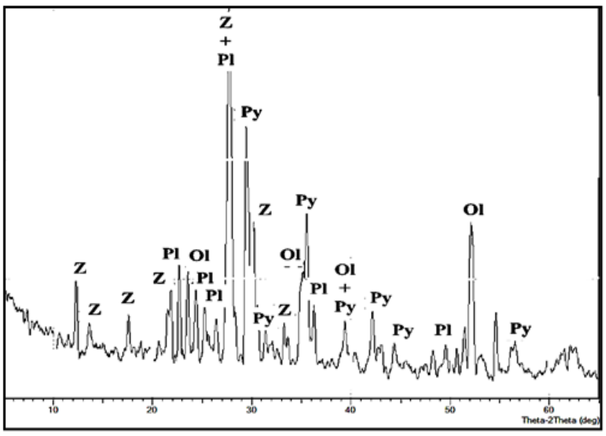

Figure 3. XRD spectrum of volcanic tuff
Z: zeolitic minerals, Pl: plagioclase, Py: pyroxene,and Ol: olivine

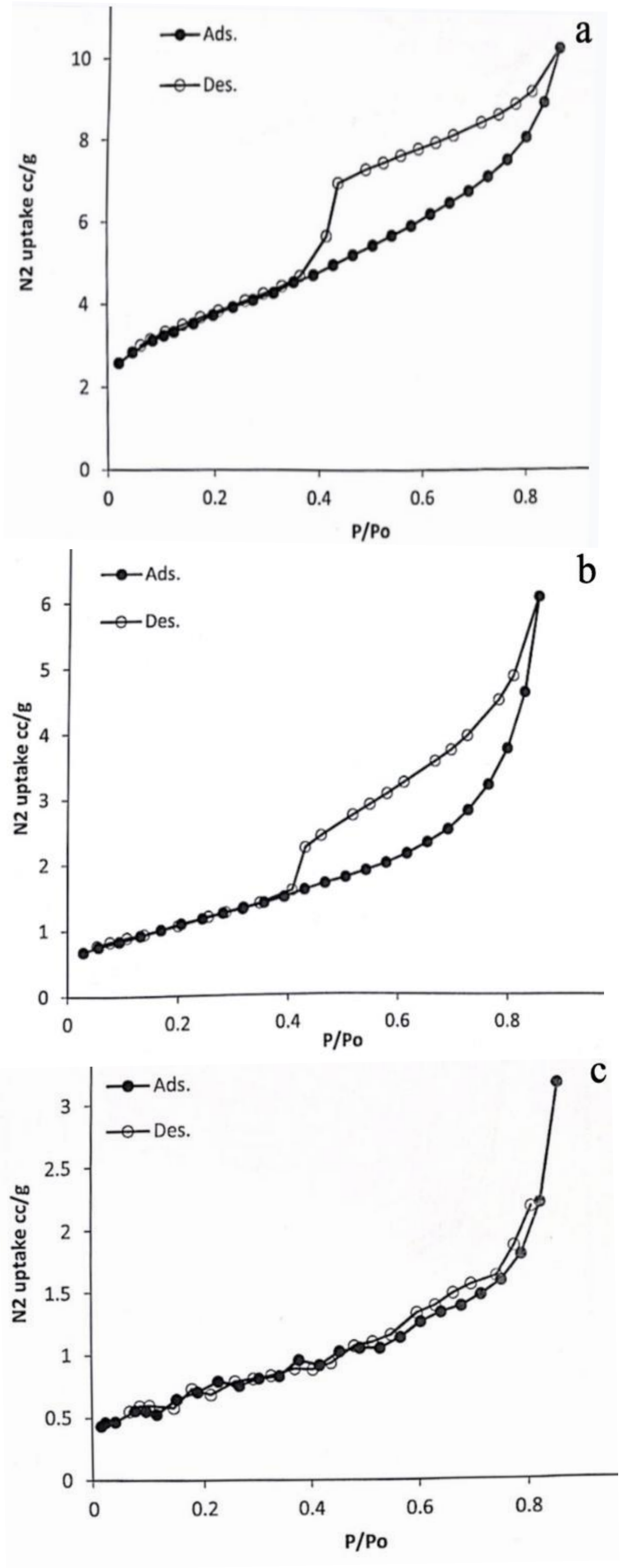

Figure 4. Adsorption/desorption curves of (a) wood ash, (b) date pit ash, and (c) volcanic tuff

Table 1. Major elements composition of absorbent materials

Wt.%	Al_2O_3	CaO	Cl	Fe_2O_3	K_2O	L.O.I	MgO	Na_2O	P_2O_5	SiO_2	SO_3	TiO_2
Wood Ash	1.68	36.4	0.798	1.6	16.6	26.14	3.59	1.76	3.17	4.87	1.93	0.75
Date Pit Ash	6.39	10.3	1.61	5.77	18.5	3.56	9.05	2.03	18.20	19.50	3.65	0.64
Volcanic Tuff	15.60	10.50	-	13.50	1.10	4.85	6.06	2.91	0.43	42.50	0.34	1.86

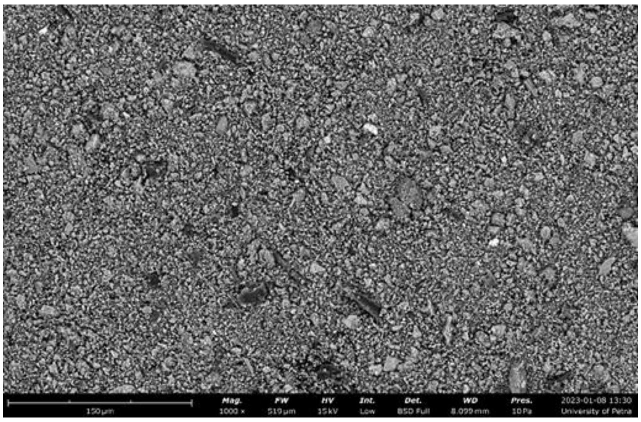

Figure 5. SEM micrograph of wood ash

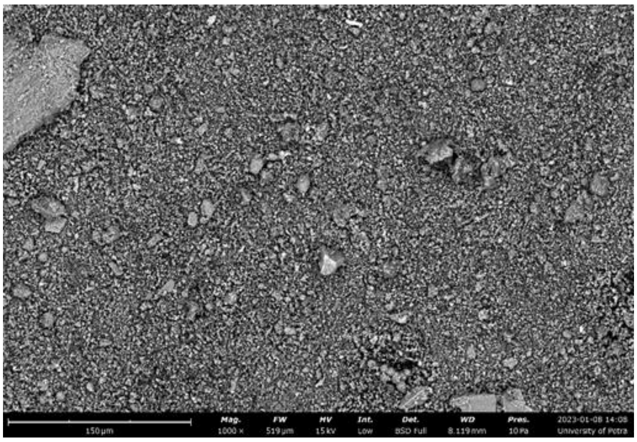

Figure 6. SEM micrograph of date pit ash

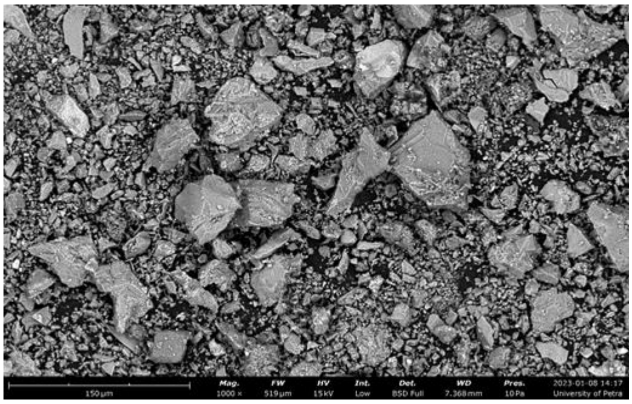

Figure 7. SEM micrograph of volcanic tuff

3.2 Evaporation test results

Figure 8 shows the average temperature, relative humidity, and wind speed changes daily during the experiment. The average temperature ranged between 18℃ and 9℃. The average relative humidity was around 30%–20%. The average wind speed ranged from 9.4 to 10 kph. The temperature was higher at the beginning of the test than at the end. The variations in relative humidity exhibit a linear decrease with increasing wind speed. Figure 9 shows the evaporation rate results for the soil before and after the addition of the absorbent materials. The results show that the evaporation rate in the free soil decreased from one day to another, mainly due to a decrease in temperature. The changes in the evaporation rate for soil samples after adding absorbent materials over days are basically the same pattern, and the curve shape similarity is high. The evaporation rate decreased considerably with the addition of the three absorbent materials.

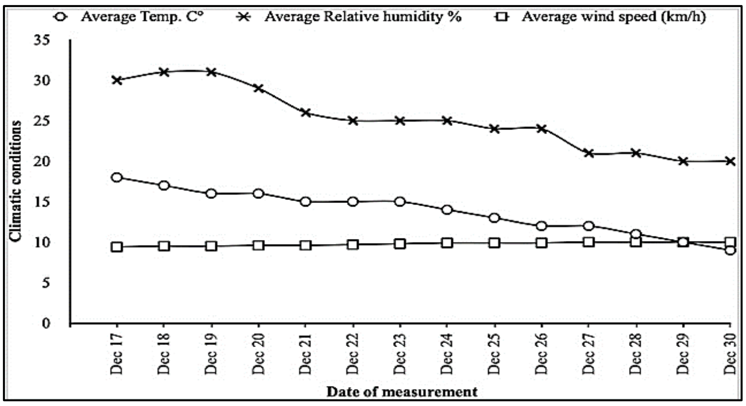

Figure 8. Variations in daily average temperature, relative humidity, and wind speed

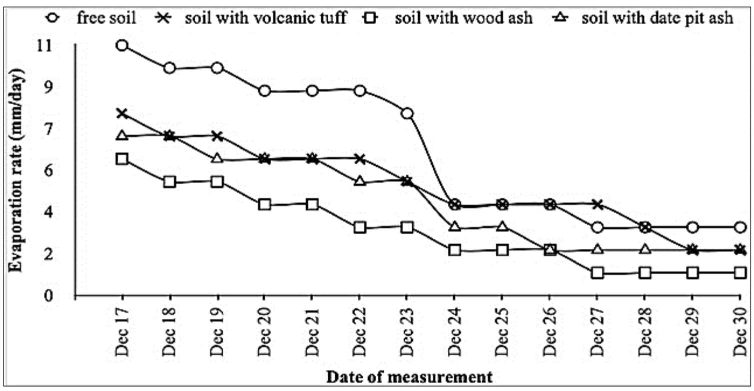

Figure 9. Variations in daily evaporation rates

According to characterization investigations, wood and date pit ash are more effective at retaining soil water than volcanic tuff due to their small grain size, high porosity, low density, and large surface area. However, temperature is the most influential factor in determining the rate of evaporation; with the addition of absorbent materials, the residual water content of the soil increases by improving the soil structure. According to Trivedi et al. [29], low-density ash and porous materials can enhance the microscopic pore structure and increase the specific surface area to absorb water. This study is also in agreement with the previous studies, which found that volcanic tuff and biomass ash have efficiency for soil water conservation and reducing the evaporation rate [19, 26, 27, 30-35].

Determining the optimal material for reducing soil evaporation is contingent upon the specific geographic location under consideration. For instance, in Jordan, where volcanic tuff abounds across expansive areas, it emerges as a prominent candidate due to its widespread availability and cost-effectiveness. Similarly, in the Gulf region, the abundance of date palm trees results in a copious supply of date pits, rendering them a viable option for soil moisture conservation [36]. The sheer ubiquity of date palms in this region underscores the potential of date pit ash as a potent medium for reducing evaporation rates. Conversely, regions such as those in the heart of Africa exhibit greater availability of wood ash, presenting a viable alternative for soil evaporation mitigation [37]. The abundance of wood resources in these areas makes wood ash a feasible option for curbing moisture loss from soil surfaces. Thus, tailoring the choice of evaporation-reducing materials to the specific environmental context ensures optimal efficacy and resource utilization across diverse geographical locales.

4. CONCLUSIONS

In order to investigate the effects of volcanic tuff, wood ash, and date pit ash on the reduction of soil water evaporation, thereby conserving water resources used in irrigation, an evaporation experiment has been carried out on soil by adding these materials. The results show that adding absorbent materials to the arid soil can reduce water evaporation up 30%. Wood ash had the lowest reduction rate during the test period compared to date pit ash and volcanic tuff due to its small grain size, high porosity, low density, and large surface area. A positive relationship between temperature and the material's ability to reduce evaporation was also identified. The proposed method of incorporating absorbent materials into arid soils shows promise as a practical and environmentally friendly approach to address water scarcity challenges in agriculture. Further research could explore the scalability, economic viability, and long-term impact of implementing these absorbent materials in real-world agricultural settings. However, volcanic tuff, wood ash, and date pit ash have various applications that provide practical, environmentally friendly solutions for agricultural aspects, waste water management, and environmental conservation efforts. However, our natural experiment design underscores the adaptability and perceptible efficacy of incorporating natural materials to diminish soil evaporation. This approach hinges predominantly on the inherent characteristics of the internal structures. Alterations to these internal structures through processes such as calcination necessitate further investigation to comprehensively assess their impact on evaporation reduction.

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