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Use of marble sludge and biochar to improve soil water retention capacity

Uso de lodo de mármol y biochar para mejorar la capacidad de retención de agua del suelo
Uso de lamas residuais de mármore e biochar para melhorar a capacidade de retenção de água do solo

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ABSTRACT

Agriculture and mining are the most important economic activities in the province of Almería (SE Spain) and generate large amounts of waste. Almería is one of the driest regions in Europe, and its water resources come mainly from groundwater. The high water consumption of greenhouses (between 5000 and 6000 m^3 ha^{-1} y^{-1}) has resulted in a sharp decline of water table levels and a worsening of water quality. Therefore, it is necessary to implement actions that lead to the more efficient use of irrigation water. The objective of this study was to evaluate the effect of two waste types (marble sludge and biochar from greenhouse plant debris) on the soil water holding capacity. Three treatments were performed in pots using two of the most common soils in greenhouses. A lettuce seedling was planted in each pot, and the volumetric water content was periodically controlled. The first treatment contained 600 g of soil, the second treatment contained 200 g of marble sludge at the bottom and 400 g of soil on the surface, and the third treatment contained 150 g of marble sludge at the bottom, 50 g of biochar in the middle and 400 g of soil on the surface. The results showed that the use of marble sludge, biochar and the combination of both waste types increased water holding capacity. The volumetric water content was relatively high for a longer time, allowing for a reduction in watering frequency and enabling more efficient water use. The waste applications were most effective in the soil with a thicker texture and lower evaporation rate.

RESUMEN

La agricultura y la minería son las actividades económicas más importantes en la provincia de Almería (SE, España) y generan grandes cantidades de residuos. Almería es una de las regiones más secas de Europa y sus recursos hídricos provienen principalmente de aguas subterráneas. El alto consumo de agua de los invernaderos (entre 5000 y 6000 m^3 ha^{-1} *año*$^{-1}$*) ha dado como resultado una disminución de los niveles freáticos y un empeoramiento de la calidad del agua. Por lo tanto, es necesario implementar acciones que conduzcan al uso más eficiente del agua de riego. El objetivo de este estudio fue evaluar el efecto de dos residuos (lodo de mármol y biochar procedente de restos de plantas de invernadero) sobre la capacidad de retención de agua del suelo. Se realizaron tres tratamientos en macetas usando dos de los suelos más comunes en invernaderos. Una plántula de lechuga se plantó en cada maceta y el contenido volumétrico de agua fue controlado periódicamente. El primer tratamiento contenía 600 g de suelo, el segundo tratamiento contenía 200 g de lodo de mármol en la parte inferior y 400 g de suelo en la superficie, y el tercer tratamiento contenía 150 g de lodo de mármol en la parte inferior, 50 g de biochar en una zona intermedia y 400 g de suelo en la superficie. Los resultados mostraron que el uso de lodo de mármol, biochar y la combinación de ambos residuos aumentó la capacidad de retención de agua. El contenido de agua volumétrico fue relativamente alto durante más tiempo, permitiendo una reducción en la frecuencia de riego y un uso más eficiente del agua. Los residuos fueron más eficaces en el suelo con una textura más gruesa y menor tasa de evaporación.*

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RESUMO

A agricultura e a exploração mineira são as atividades económicas mais importantes na região de Almería (SE, Espanha) e geram grandes quantidades de resíduos. Almería é uma das regiões mais secas da Europa, e os seus recursos hídricos provêm principalmente de águas subterrâneas. O alto consumo de água nas estufas (entre 5000 e 6000 m^3 ha^{-1} ano^{-1}) resultou numa diminuição dos níveis do aquífero e num decréscimo da qualidade da água. Por esta razão, é necessário implementar ações que conduzam a um uso mais eficiente da água de rega. O objetivo deste estudo foi avaliar o efeito dos resíduos (lamas residuais de mármore e biochar proveniente dos restos de plantas de estufas) na capacidade de retenção de água do solo. Realizaram-se três tratamentos em ensaios em vaso, usando dois dos solos mais comuns utilizados em estufas. Uma plântula de alface foi plantada em cada vaso, e o teor volumétrico da água foi controlado periodicamente. O primeiro tratamento continha 600 g de solo, e o segundo tratamento continha 200 g de lamas residuais de mármore na parte inferior e 400 g de solo na parte superior, e o terceiro tratamento continha 150 g de lamas de mármore na parte inferior, 50 g de biochar num zona intermédia e 400 g de solo na zona superficial. Os resultados mostraram que o uso de lamas de mármore, biochar e a combinação de ambos os resíduos aumentou a capacidade de retenção de água no solo. O teor volumétrico da água foi relativamente elevado durante mais tempo, permitindo uma redução da frequência de rega e um uso mais eficiente da água. Os resíduos foram mais eficazes no solo com textura mais grosseira levando a uma menor taxa de evaporação.

KEY WORDS
Soils, irrigation, wastes, saving water.

PALABRAS CLAVE
Suelos, riego, residuos, ahorro de agua.

PALAVRAS-CHAVE
Solos, rega, resíduos, poupança de água.

1. Introduction

Agriculture, mining and industry are human activities that generate significant amounts of waste with a high environmental impact. Agriculture and mining are the fundamental pillars on which the economy of the province of Almería (SE Spain) rests. Almería has almost 30 x 10^3 ha of greenhouses and over 6.6 x 10^3 ha of marble quarries. In the 2012-2013 period, the greenhouse crop production in Almería amounted to 2.6 x 10^6 t, with a value of 1528 x 10^6 € (Valera et al. 2014). In 2013, approximately 3 x 10^6 t of marble was extracted, with a value of 16 x 10^6 € (Estadística Minera de España 2013). The average annual water consumption in greenhouses is in the range of 5000–6000 m^3 ha^{-1} y^{-1} (Céspedes et al. 2009), mostly from underground sources (79.7%). Because Almería is one of the driest regions in Europe, with a mean annual rainfall between 200 and 300 mm, the extraction of water from aquifers widely exceeds the recharge, which leads to a gradual depletion of aquifers, seawater intrusion and a worsening of the groundwater quality (Pulido-Bosch et al. 1992; Sánchez-Martos et al. 1999; Molina-Sánchez et al. 2015). Therefore, a more efficient use of irrigation water is essential.

The province of Almería generates approximately 65 x 10^4 t of vegetable waste from greenhouses (Tolón and Lastra 2010) and between 10 x 10^6 and 13 x 10^6 t y^{-1} of sludge from cutting and polishing marble. The marble sludge has a high water holding capacity available to plants (0.256 dm^3 kg^{-1}), and it is useful in the ecological restoration of marble quarries (Simón et al. 2014; Gómez et al. 2015). The biochar produced from greenhouse plant waste could improve both the water holding capacity (Laird et al. 2010; Castellini et al. 2015; Ajayi et al. 2016; Obia et al. 2016) and the development of roots (Sohi et al. 2009; Bruun et al. 2014). The objective of the present work was to assess the effect of marble sludge and biochar from greenhouse organic waste on the water holding capacity of two common greenhouse soils, the frequency of irrigation and the amount of water needed. The results could lead to a more rational consumption of irrigation water and could transform wastes with high environmental impacts into resources.

2. Material and Methods

2.1. Soils and wastes

Two typical soils used in greenhouses in the province of Almería, one with a sandy loam texture (S1) and other with a sandy texture (S2) were selected for this study. The waste types were sludge from cutting and polishing marble from quarries of Macael (M), and biochar (B) that was obtained by pyrolysis (at 500 ºC) of greenhouse plant debris (Gaskin et al. 2008). The soils and waste were air dried and sieved to 2 mm. The pH was measured in a 1:2.5 solid:water suspension. The saturation extracts of soils and waste were prepared (US Salinity Laboratory Staff 1954), the solution was vacuum pumped and the electrical conductivity (EC) was measured. The bulk density (BD) was estimated using a cylinder of known volume. Total carbon and nitrogen were analysed by complete combustion at high temperature (1200 ºC) in an ELEMENTAR Vario Micro CHNS Instrument, Elementar Analysensysteme GmbH, Hanau, Germany. The calcium carbonate equivalent ($CaCO_3$) was estimated manometrically (Williams 1948). The organic carbon (OC) was determined by taking the difference between total carbon and inorganic carbon from $CaCO_3$. The total concentration of potassium and phosphorus were determined by X-ray fluorescence (XRF) in a Bruker Pioneer Instrument. The particle size distribution was determined using the pipette method (Loveland and Whalley 1991). The gravimetric water content of the wastes and soils to matric potentials of 33 kPa (ω_{33}) was determined using a pressure plate (Gardner 1965). The volumetric water content (θ_{33}) was estimated from the equation: θ_{33} ($dm^3\ m^{-3}$) = $10^3 \times \omega_{33} \times$ BD.

2.2. Greenhouse experiment

In pots with 8.4 cm diameter and 11 cm deep (609 cm^3), three treatments with each soil were applied. The first treatment contained 600 g of soil (S), the second treatment contained 200 g of marble sludge at the bottom and 400 g of soil on the surface (SM), and the third treatment contained 150 g of marble sludge at the bottom, 50 g of biochar in the middle and 400 g of soil on the surface (SBM). The volumetric water content of the treatments was determined using the ML2x probe (ΛT instrument), which has 10 cm long moisture sensors. The depth of the treatments was about 10 cm, so the probe measured the moisture content throughout its thickness. To assess the accuracy of the moisture measurements with the ML2x probe, all treatments with S1 and S2 soils were weighed dry (PS) and then saturated with water, allowed to drain for 24 hours and weighed wet (PH). Wet treatments were left to dry and were regularly weighed. After each weighing, the volumetric water content was measured with the ML2x probe (θ_p). Likewise, at each weighing, the gravimetric moisture content (ω_w) was estimated by taking the difference between PH and PS, and the volumetric moisture content (θ_w) was calculated from the equation:

(1)

$$\theta_w\ (dm^3 m^{-3}) = \frac{\omega W}{\frac{Ps}{BDs} + \frac{Pm}{BDm} + \frac{Pb}{BDb}} x\ 10^3$$

where Ps, Pm and Pb are the weights (g) and BDs, BDm and BDb are the bulk densities (g cm^{-3}) of soil, marble sludge and biochar of each treatment, respectively. In both soils, θ_p and θ_w were significantly and linearly related by the equations:

(2)

Soil 1: θ_p ($dm^3\ m^{-3}$) = 1.084 θ_w ($dm^3\ m^{-3}$) – 10.636
$r^2 = 0.976$
$p < 0.001$

(3)

Soil 2: θ_p ($dm^3\ m^{-3}$) = 0.981 θ_w ($dm^3\ m^{-3}$) + 6.889
$r^2 = 0.974$
$p < 0.001$

The slope of the straight line and the determination coefficient of equations (2) and (3) were close to the unity, indicating that the ML2x probe is quite accurate for measuring the volumetric soil moisture.

Two experimental operating modes, conducted simultaneously between 1st April and 1st June, were designed. For both operating modes, θ_p was first measured one hour after irrigation, once drainage had ceased. Subsequently, θ_p was measured periodically until its value advised a new irrigation, and the above procedure was repeated. In the first experiment, S1 soil treatments (S1, S1M and S1BM) were made in triplicate, and in each of them a seedling of *Lactuca sativa* L. was sown. In each irrigation 150 cm^3 of water was added, although the irrigation frequency differed. The first replicate (1S1, 1S1M and 1S1BM) received a new irrigation when θ_p at 1S1 was about 175 dm^3 m^{-3} (75% of θ_{33} estimated from ω_{33}, which was 241 dm^3 m^{-3}), the second replicate (2S1, 2S1M, 2S1BM) received a new irrigation when θ_p at 2S1 was about 125 dm^3 m^{-3} (50% of θ_{33}) and the third replicate (3S1, 3S1M, 3S1BM) received a new irrigation when θ_p at 3S1 was about 90 dm^3 m^{-3} (35% of θ_{33}) and the lettuce showed the first signs of wilting. The total water retained by each soil during the experiment could be calculated by the sum of the differences between the θ_p before and after each irrigation.

The second experiment aimed to analyse the water needed to maintain a very high θ_p, which is a very common practice in the greenhouses of Almería. The S2 soil treatments (S2, S2M and S2BM), in which a seedling of *Lactuca sativa* L. was also sown, were irrigated with 150 cm^3 of water when the θ_p in each of them was about 200 dm^3 m^{-3} (90% of θ_{33} estimated from ω_{33}, which was 222 dm^3 m^{-3}). At the end of the experiment and after the last irrigation (from 1st to 10th of June 2015), the θ_p was measured daily to determine how each treatment was drying.

Both experimental operating modes were performed in triplicate. Distilled water was used in order to prevent changes in the chemical composition (osmotic potential) of the irrigation water.

Two months after the start of the experiments, the lettuce plants were carefully removed. The roots and leaves were separated and carefully washed with distilled water and then oven dried at 65 ºC for 72 hours. Finally, the shoot and root dry biomasses were weighed to determine plant growth in each treatment.

2.3. Statistical analysis of data

The mean values and standard deviation of three replicates (n = 3) were calculated. To detect whether the differences were significant, the mean values were compared using an ANOVA (Tukey HSD test, $p < 0.05$). A correlation analysis of the different parameters was performed, and the coefficient of determination (r^2) and significance (p) were computed. All graphics and analyses were performed using Microsoft Excel and the statistical programme STATGRAPHICS Centurion XVI.

3. Results and discussion

3.1. Soils and wastes

Most of the S1 and S2 soil properties were similar (**Table 1**). Both soils were alkaline (pH > 7.5) and slightly saline (CE < 5.5 dS/m), these parameters being slightly higher in S2 and significantly different. The BD was also similar in both soils, while the OC, N, P and K content was higher in S1. Both soils were carbonated, but the $CaCO_3$ content was nearly four times higher in S2. The particle size distribution was dominated by the sand fraction (> 700 g/kg), but there were clear differences between the soils. In S1, the fine sand fraction (< 0.5 mm) was dominant, whereas in S2, the coarse sand fraction was dominant (> 0.5 mm). The silt and clay fractions were higher in S1 than in S2. These results suggest that the average pore size must have been larger in S2 than in S1. Biochar was characterized by a very high pH (~ 10) and OC content (> 650 g/kg), and N, P and K content was clearly higher than in the soils. The EC and BD values of the biochar were relatively low. Like the soils, the biochar was also carbonated, with an intermediate $CaCO_3$ content ranging between those of the S1 and S2 soils. The marble sludge was alkaline, with a pH value similar to the S2 soil. However, the other properties of the marble sludge were very different to those of the soils because the sludge was composed almost exclusively of $CaCO_3$ particles of silt and clay sizes, which resulted in low OC, N, P and K contents.

Table 1. Soils and waste properties

	Soils		Waste	
	S1	**S2**	**Biochar**	**Marble sludge**
pH	7.7 ± 0.1	8.3 ± 0.1	9.9 ± 0.1	8.6 ± 0.1
EC (dS/m)	4.5 ± 0.1	5.1 ± 0.1	0.57 ± 0.04	2.2 ± 0.1
BD (g/cm^3)	1.44 ± 0.02	1.43 ± 0.02	0.33 ± 0.02	1.19 ± 0.03
OC (g/kg)	15.3 ± 0.4	12.1 ± 0.4	651 ± 0.4	0.61 ± 0.02
$CaCO_3$ (g/kg)	58.4 ± 0.8	209 ± 15	128 ± 2	987 ± 4
N (g/kg)	1.5 ± 0.2	0.75 ± 0.09	7.3 ± 0.1	nd
P (g/kg)	3.5 ± 0.1	1.4 ± 0.1	5.8 ± 0.1	nd
K (g/kg)	13.5 ± 0.1	8.7 ± 0.1	30.9 ± 0.4	0.79 ± 0.02
CS (g/kg)	10.7 ± 1.5	537 ± 4	nm	0.11± 0.02
FS (g/kg)	722 ± 4	328 ± 4	nm	6.2 ± 0.3
S (g/kg)	151 ± 2	84.7 ± 1.5	nm	684 ± 11
C (g/kg)	116 ± 8	51.3 ± 2.3	nm	254 ± 9

EC = electrical conductivity; BD = bulk density; OC = organic carbon; N = nitrogen; P = phosphorous; K = potassium; CS = coarse sand (2-0.5 mm); FS = fine sand (0.5-0.05 mm); S = silt (0.05-0.002 mm): C = clay (< 0.002 mm); nd = not detected; nm = not measured.

3.2. Water content of the treatments

An hour after irrigation (**Figure 1A**), the θ_p in the S1 treatment was 344 ± 7 dm^3 m^{-3}, 6% greater in the S1M treatment (365 ± 5 dm^3 m^{-3}) and 18% greater in the S1BM treatment (406 ± 3 dm^3 m^{-3}). These differences between the three treatments increased as the materials dried. Thus, before irrigation, when the θ_p in the 1S1 treatment decreased to 172 ± 7 dm^3 m^{-3}, the θ_p was 29% greater (222 ± 5 dm^3 m^{-3}) in the 1S1M treatment and 56% greater (267 ± 6 dm^3 m^{-3}) in the 1S1BM treatment. When the θ_p in the 2S1 treatment before irrigation decreased to 122 ± 5 dm^3 m^{-3}, the θ_p was 70% greater (207 ± 4 dm^3 m^{-3}) in the 2S1M treatment and 106% greater (251 ± 4 dm^3 m^{-3}) in the 2S1BM treatment. Finally, when the θ_p in the 3S1 treatment decreased to 87 ± 3 dm^3 m^{-3} before irrigation and the lettuce showed the first signs of wilting, the θ_p was 92% greater (166 ± 4 dm^3 m^{-3}) in the 3S1M treatment and 172% greater (237 ± 4 dm^3 m^{-3}) in the 3S1BM treatment. Furthermore, the lettuce showed no signs of wilting in the last two treatments. These results indicate that waste and biochar, especially the combination of B and M, increased the water holding capacity of the substrate, while the θp remained relatively high over a long period of time, allowing the lettuce to show no signs of wilting. Therefore, the use of these wastes could reduce irrigation frequency.

The change in θ_p from one hour after the irrigation until the next watering (**Figure 1B**) showed that in order to maintain the θ_p at a given value, the time elapsed between irrigations increases in the direction S1 < S1M < S1BM. Thus, to maintain $\theta_p \geq 200$ dm^3 m^{-3}, S1 treatments should be irrigated every 60 hours, S1M treatments should be irrigated every 85 hours and S1BM

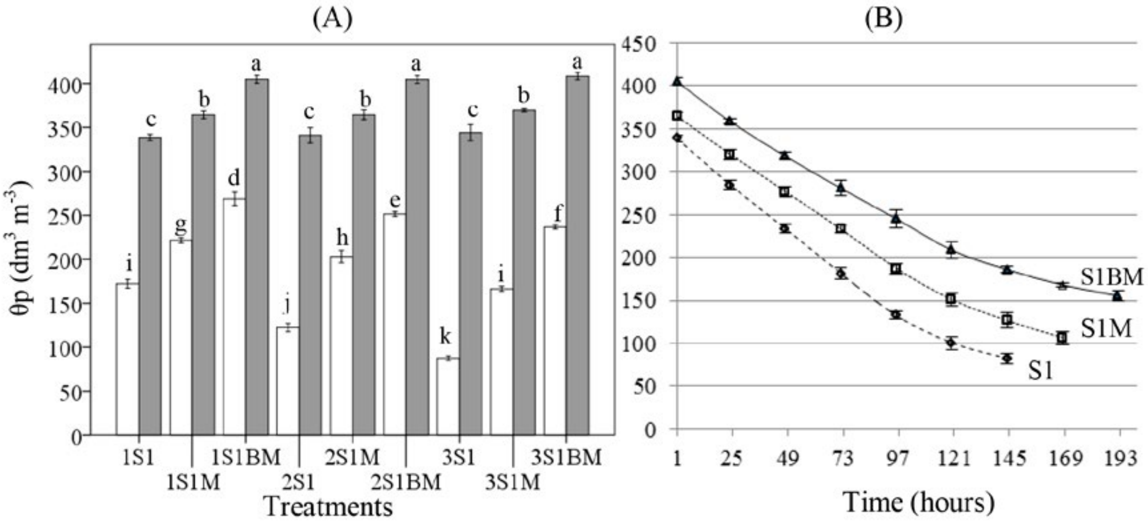

Figure 1. (A) Mean and standard deviation of the volumetric water content (θ_p) of the treatments before (white) and after (grey) each irrigation. (B) Mean and standard deviation of the θ_p between irrigations versus time elapsed. In (A), mean values followed by the same letter do not differ significantly (Tukey test, $p < 0.05$)

treatments should be irrigated every 125 hours. Compared with the S1 treatment, irrigation could be reduced by 30% in the S1M treatment and 50% in the S1BM treatment. Therefore, the use of such wastes could result in significant water saving.

In the second experiment, S2, S2M and S2BM treatments received a new irrigation when the θp in each treatment was approximately 200 $dm^3 m^{-3}$. The total water needed to maintain the θ_p, estimated by the sum of the differences between the θ_p before and after each irrigation, was 1568 ± 23 $dm^3 m^{-3}$ in the S2 treatment, almost 27% lower in the S2M treatment (1164 ± 17 $dm^3 m^{-3}$) and just over 50% lower in the S2BM treatment (724 ± 22 $dm^3 m^{-3}$). These results are similar to those obtained in the first experiment and confirm the aforementioned considerations.

The change in θ_p during progressive drying of S2 soils (**Figure 2**) indicated that to maintain the θ_p at levels greater than or equal to 200 $dm^3 m^{-3}$, S2 treatment should be irrigated every 65 hours, S2M treatments should be irrigated every 115 hours, and S1BM treatments should be irrigated every 195 hours. Compared to the S1 treatments (**Figure 1B**), the elapsed time between watering to maintain the $\theta_p \geq 200$ $dm^3 m^{-3}$ was clearly higher in S2 treatments. Therefore, the effectiveness of the waste to increase water holding capacity and maintain relatively high θ_p values tends to be greater in the S2 soil than in the S1 soil. These differences may be explained by the soil texture (**Table 1**). The S1 soil had a finer texture dominated by < 0.5 mm grain sizes (approximately 99%) and relatively high silt and clay content (approximately 25%). In contrast, the S2 soil has a coarser texture dominated by > 0.5 mm grain sizes (approximately 55%) and lower silt and clay content (approximately 14%). This textural difference may be responsible for a decrease in the capillary action in the S2 soil compared with the S1 soil, which would result in a decline in evaporation and a longer dwell time of water in the S2 soil. Therefore, the effectiveness of these wastes tends to increase in sandy soils (Ulyett et al. 2014; Omondi et al. 2016), which are widespread in the greenhouses of Almería.

3.3. Plant growth

In the S1 soil, the shoot and root dry biomasses significantly decreased as the frequency of watering decreased from 1S1 to 3S1 (**Figure 3**), confirming that water stress decreased plant productivity.

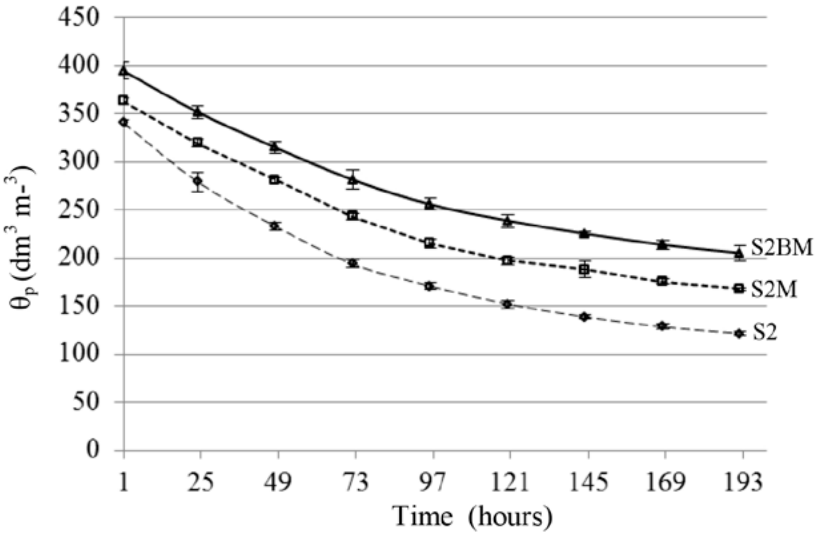

Figure 2. Mean and standard deviation of the volumetric water content (θ_p) in each treatment during progressive drying in experimenting with S2 soil versus time elapsed.

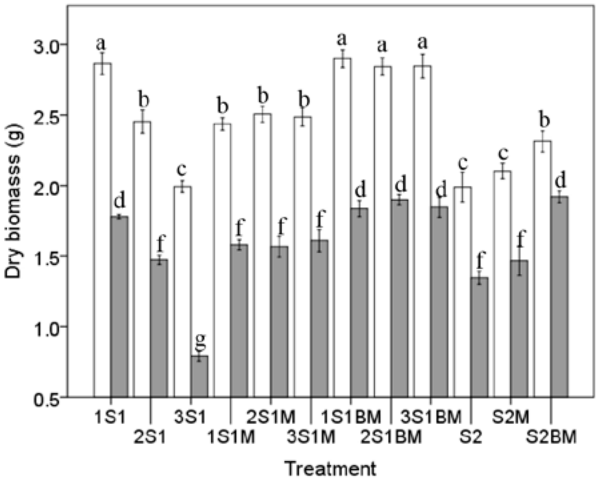

Figure 3. Mean and standard deviation of the dry biomass of shoots (white) and roots (gray) of lettuce versus treatment. To shoot and root separately, different letters indicate significant differences (Tukey test, *p* < 0.05).

However, the shoot and root dry biomasses were similar in 1S1M, 2S1M and 3S1M treatments, indicating that marble sludge effectively increased the soil water holding capacity so that lettuce did not appear to suffer water stress even when irrigations were less frequent (3S1M). In the S1BM treatment, the results were similar to results obtained in the S1M treatment, but the biomasses were greater in the S1BM treatment. Given that the treatments were watered with distilled water without any added nutrients, differences in dry biomass of treatments with both soils could be justified by the nutrient content (N, P and K, **Table 1**) in the wastes (very high in the biochar and absent or very low in marble sludge) and soils (S1 > S2). The higher nutrient content may have encouraged a greater uptake of nutrients and further development of the plants (Xu et al. 2012; Haider et al. 2015; Vaughn et al. 2015; Olmo et al. 2016).

4. Conclusions

Biochar, marble sludge and, especially, the combination of both waste types significantly increased the water holding capacity of soils. The θ_p was relatively high for a longer period of time, which could allow for reduced watering frequency. The significant water savings would enable the more efficient use of the scarce water resources in the province of Almería. The effectiveness of these waste types to reduce irrigation water increased in soils with coarser texture, which reduced evaporation rate.

In any case, these are preliminary findings that should be confirmed in the field with fertigation. Because rooting depth varies by crop type, future research in the field should address the depth to which waste should be placed for best results.

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