CSIRO PUBLISHING

RESEARCH PAPER
https://doi.org/10.1071/SR20327

SOIL RESEARCH

Influence of the physical properties of pumice and biochar amendments on the soil's mobile and immobile water: implications for use in saline environments

Chao Kong[A,*], Marta Camps-Arbestain[A] and Brent Clothier[B]

For full list of author affiliations and declarations see end of paper

*Correspondence to:
Chao Kong
School of Agriculture and Environment, Private Bag 11222, Massey University, Palmerston North 4442, New Zealand
Email: 1140586458@qq.com

Handling Editor:
Etelvino Novotny

Received: 21 November 2020
Accepted: 30 September 2021
Published: 17 November 2021

Cite this:
Kong C et al. (2022)
Soil Research, 60(3), 234–241.
doi:10.1071/SR20327

ABSTRACT

Context. Biochar and pumice have potential to improve soil water retention and mitigate salinity. However, little is known about their effect on salt transport in sandy soils. **Aims.** We investigated the influence of the porosity and pore size distribution of soil amendments with pumice and biochar on the mobile water content of a New Zealand sandy soil. **Methods.** Pumice and biochar (1.5-cm, 3-cm and 6-cm in diameter, Ø) were characterised using scanning electron microscope technology. The fraction of mobile water present in these amendments, previously added to a sandy soil at different application rates and particle sizes, was determined using a tracer (Na^+) technique. **Key results.** (1) Pumice exhibited a wider pore-size span than biochar; and (2) both materials had a predominance of pores with Ø < 30 μm; but (3) the total porosity in pumice and biochar was not significantly different; (4) pumice had a significantly larger ($P < 0.05$) mean absolute micro-scale porosity than biochar; and (5) a significantly greater ($P < 0.05$) relative resident Na^+ concentration than biochar, irrespective of the particle size. **Conclusions.** These results reflect a larger fraction of the mobile water in pumice than that of biochar under near-saturated conditions, irrespective of the biochar particle size; and this increased as the pumice particle size increased. **Implications.** While both materials are expected to contribute to water retention and thus might alleviate salt-stress by diluting salt concentration, pumice may perform better than this specific biochar on improving the retention of plant-available water.

Keywords: dilution, miscible displacement, mobile-water fraction, particle size, physical properties, porosity, salinity, scanning electron microscopy.

Introduction

The sustainability of agriculture in arid regions is challenged by the limited availability of water, and the need to manage salinity in soils and irrigation-water. This demands long-term interventions, both economically and environmentally (Alon *et al.* 2006). Despite the magnitude of these challenges, there are opportunities to overcome them by further exploring innovative techniques that alleviate salt and plant-water stress (Abou-Baker and El-Dardiry 2016). One such potential option is the use of amendments, such as adding either pumice or biochar to soils. Potentially, these can contribute to improving the physical, chemical and biological properties of salt-affected soils, while promoting better plant growth (Saifullah *et al.* 2018). However, a deeper knowledge of the influence of the physical properties of the amendments is needed, as well as that of the impact of their particle size and application rate on soil water retention so that their value in ameliorating soil salinity is better understood.

Both materials have in common the fact that they are very porous. For biochar, this is particularly the case when produced from woody material (Waldron 2014). The porosity of pumice (64–85% by volume) is generated by air bubbles created during its formation, which give this material a low bulk density (0.35–0.65 g cm^{-3}), and large pore-size span (from micrometre to millimetre) (Ersoy *et al.* 2010; Cekova *et al.* 2013). The physical properties of biochar mainly depend on the type of feedstock, which is influenced by the plant cellular structure, plus the type of pyrolyser, highest heating temperature of pyrolysis, residence time (Rasa *et al.* 2018) and activating agents. Biochar has been reported to have a bulk density ranging from 0.06 to 0.7 g cm^{-3}, with a specific surface area from 50 to 630 m^2 g^{-1} (Rajkovich *et al.* 2012), while its pore size distribution can vary greatly, ranging from sub-nanometre to hundreds of microns (Brewer *et al.* 2014). The physical properties of these amendments can directly or indirectly influence soil properties and plant growth.

Although the ability of pumice (Malekian *et al.* 2012) and biochar (Herath *et al.* 2013) to retain soil water has been reported, the mechanistic understanding of how their use affects water-borne salt transport in soils under arid conditions remains largely unclear (Noland *et al.* 1992; Lura *et al.* 2004; Batista *et al.* 2018). Given that this is strongly related to the influence of these materials on the soils mobile–immobile water fractions, we aimed to evaluate how the physical properties of a pumice and a biochar (i.e. particle size and application rate) affected their mobile–immobile water when added to a sandy soil. Our objectives were two-fold:

- We first characterised the porosity and pore-size distribution of a pumice from New Zealand's central North Island, and a biochar produced from willow wood chips at a highest heating temperature of 350°C. We used a low-temperature biochar to minimise the amount of ash, given that salts in the ash can contribute to soil salinity when applied to soils in arid environments.
- We then investigated the amount of mobile water present in these amendments (previously added to a sandy soil at different rates and particle sizes) using a tracer (Na^+) during miscible displacement experiments.

Materials and methods

Preparation of the experimental material

Pumice was taken from the Tongariro National Park New Zealand (39°12′36.5″S, 175°40′55.5″E), and was washed with deionised water, then dried at 30°C for 72 h to a constant weight prior to its use. The biochar was produced from weeping-willow chips (*Salix matsudana* L.) using a rotary kiln pyrolyser (25-L retort), at heating rate ca. 10°C min^{-1} and a highest heating temperature of 350°C, which was held for 15 min. Both pumice and biochar were categorised into three different particle sizes (1.5-, 3- and 6-cm in diameter, Ø). The biochar was crushed before the particle size screening. Both materials were further milled to achieve a particle size < 0.3 mm for chemical analysis. The sandy soil (96.6% sand) for the miscible displacement experiment was obtained from the sand dunes at Himatangi Beach New Zealand (40°23′54.6″S, 175°13′33.8″E) and was air dried before use. The mineralogy of the sandy soil was predominantly quartz and feldspar (Claridge 1961). An artificial saline solution was prepared using Na_2SO_4, $CaCl_2$, NaCl and $MgSO_4$ salts at the following concentrations 0.285, 0.517, 2.865 and 0.924 g L^{-1}, respectively. The final solution had an electrical conductivity (EC) of 6.4 dS m^{-1} and a Na^+ concentration of 2300 mg L^{-1}.

Scanning electron microscopy (SEM) analysis

For measurements of porosity (pores > 300 nm Ø) and pore size distribution of pumice and biochar, surface and cross-section samples were mounted on 0.5″ (1.27 cm) aluminium specimen stubs equipped with SEM carbon foils (Agar scientific, UK). The gold coating was applied to samples after air drying at 40°C for 24 h. Micrographs were taken on a FEI Quanta 200 Environmental Scanning Electron Microscope (Quanta, Oregon, USA) at a magnification ranging from 60× to 260×, with an acceleration voltage of 20 kV. The SEM images were manually corrected with the use of Photoshop CS5 (Adobe) to remove obvious debris and darken pores, which contained either foreign material or pore sidewalls. Pore count, porosity and pore size were determined with the software ImageJ (ver. 1.49s, National Institutes of Health, http://imagej.nih.gov/ij/) using the gij_Pore Analysis plugin (Impoco *et al.* 2006). An arithmetic average of the data from six different SEM images was taken for each parameter. Pore sizes were functionally divided into four categories: (1) ultramicropores (Ø < 3 µm); (2) micropores (Ø of 3–30 µm); (3) mesopores (Ø of 30–100 µm); and (4) macropores (Ø > 100 µm) (Landis *et al.* 1990; Drzal *et al.* 1999). The macropores enable soil drainage and aeration, the mesopores contribute to soil-water conductivity, the micropores provide soil-water retention, with the water retained in ultramicropores being unavailable for plant use (Landis *et al.* 1990; Drzal *et al.* 1999).

Miscible displacement analysis

Measurements of the pore volume of materials

The pore volume (PV) of the materials (Table 1) were estimated by immersing a known volume of the amendments (v_i) in water for 72 h and looking at the corresponding increases in weight (m_i). In this experiment, since the volume of the amendment only accounts for a small part of the total soil volume, we used the PV of sandy soil to represent the PV of the soil after amendment addition hereafter.

Measurement of the mobile water fraction in pumice and biochar

The mobile water fraction (θ_m) of pumice and biochar during near-saturated flow was determined following the tracer technique proposed by Clothier *et al.* (1992) with some modifications as detailed below, and in the

Table 1. Pore volume and Na^+ concentration of pumice, biochar, and sandy soil.

	Pore volume (v/v)	Na^+ (mg cm^{-3})
Pumice		
Pu-1.5	0.16 ± 0.02b	0.01 ± 0.01a
Pu-3	0.19 ± 0.02a	0.01 ± 0.01a
Pu-6	0.22 ± 0.01a	0.02 ± 0.01a
Biochar		
Bi-1.5	0.35 ± 0.06a	0.03 ± 0.01a
Bi-3	0.29 ± 0.04a	0.04 ± 0.01a
Bi-6	0.31 ± 0.03a	0.04 ± 0.01a
Sandy soil		
S	0.31 ± 0.03	0.50 ± 0.02

Note: values are mean ± s.d. of three replicates. Mean values with different letters indicate significant differences within the same material (Duncan's test, $P < 0.05$).
Pu-1.5, pumice with 1.5-cm Ø; Pu-3, pumice with 3-cm Ø; Pu-6, pumice with 6-cm Ø; Bi-1.5, biochar with 1.5-cm Ø; Bi-3, biochar with 3-cm Ø; Bi-6, biochar with 6-cm Ø; S, sandy soil.

Supplementary information. Briefly, pumice and biochar of three particle sizes (1.5-, 3- and 6-cm Ø) were separately added to the sandy soil at three application rates (3, 6 and 12%, v/v basis). Thereafter, 1 L of mixed sandy soil and amendment (in triplicate) was added to a 2.3-L plastic container (16.5 × 15.5 × 9 cm^3) with free-water drainage at its bottom. Initial charging of the immobile fraction θ_{im} was achieved by first wetting the soil with two PV of deionised water until near-saturated conditions prevailed. The system was then rapidly re-wet with an artificial saline solution containing a tracer (Na^+) at the C_m concentration of 2300 mg L^{-1}. A total volume of eight PV of saline solution was supplied to the soil. Subsequently the bottom 5-cm of soil was sampled. Pumice and biochar were completely separated from the sandy soil and then dried at 30°C for 72 h to a constant weight. Prior to chemical characterisation, pumice and biochar particles, at the beginning and at the end of the experiment, were ground to a size < 0.25 mm. After homogenisation, deionised water at a 1:5 w/v solid:water ratio was added to the ground material. The suspension was then shaken on an end-to-end shaker for 2 h and stood overnight. Thereafter, it was filtered through a Whatman no. 42 filter paper. The concentration of Na^+ in the water soluble-extract (hereafter referred to as C^*) was measured using a Microwave Plasma Atomic Emission Spectrometer (MP-AES). The ratio of the measured resident solute concentration C^* to applied solution concentration C_m, C^*/C_m, was the fraction of material's water that was effectively mobile. The concentration of Na^+ of pumice, biochar and the sandy soil at the beginning of the experiment are reported in Table 1, where it is shown that concentrations, on volume basis, were > 10 times smaller in the amendments than in the sandy soil. With this methodology, field irrigation was simulated using a burette as the wetting system through which the amount of water added to the soil and the rate of soil wetting could be accurately controlled.

Data processing and statistical analysis

Data processing was performed with Microsoft Excel 2019. Statistical analyses were carried out using the SPSS ver. 14.0 software package (IBM, Armonk, New York, USA) and GraphPad Prism 8 software. A one-way ANOVA with Duncan's test was used to detect significant differences (at $P < 0.05$) between the treatment means for parametric data (non-SEM data). The Kruskal–Wallis and Nemenyi tests were used to detect significant differences (at $P < 0.05$) between the treatment means for SEM data.

Results

Pore characteristics of pumice and biochar

Pumice exhibited a pore-size span ranging from 0.5 to 13 000 μm (Table 2). The maximum pore sizes observed under SEM followed the order of Pu-1.5 (5 mm) < Pu-3 (10 mm) < Pu-6 (13 mm). The pore-size span of biochar was smaller than that of the pumice and ranged from 0.3 to 651 μm (Table 2). The maximum pore size seen under SEM followed the order of Bi-1.5 (0.4 mm) < Bi-3 (0.5 mm) < Bi-6 (0.7 mm). There were no evident differences in the minimum pore sizes of either pumice, or biochar, between the three particle sizes. Significant differences ($P < 0.05$) in average pore sizes of the pumice were only found between

Table 2. Pore size span and average pore size of pumice and biochar under three different particle sizes (1.5-, 3- and 6-cm in diameter) based on the scanning electron microscope inspections.

	Pore size span (μm)	Average pore size (μm)	*n*
Pumice			
Pu-1.5	0.5–4992	497.1 ± 144.2b	3140
Pu-3	1.7–9625	1004.1 ± 557.5ab	3804
Pu-6	0.8–13 308	1843.9 ± 837.4a	3340
Biochar			
Bi-1.5	0.3–368	20.9 ± 13.9a	1732
Bi-3	0.3–453	18.5 ± 11.7a	2069
Bi-6	0.5–651	21.2 ± 12.6a	1950

Note: *n* is the number of pores. Data were analysed by Kruskal–Wallis and Nemenyi tests using the SPSS ver. 14.0 software package (IBM, Armonk, New York, USA) and expressed as mean ± s.d. Mean values with different letters indicate significant differences within the same material ($P < 0.05$).
Pu-1.5, pumice with 1.5-cm Ø; Pu-3, pumice with 3-cm Ø; Pu-6, pumice with 6-cm Ø; Bi-1.5, biochar with 1.5-cm Ø; Bi-3, biochar with 3-cm Ø; Bi-6, biochar with 6-cm Ø.

Pu-1.5 (492 μm) and Pu-6 (1844 μm) (Table 2). For biochar, no significant differences in the average pore sizes were detected between the three particle sizes. The average pore size value under each particle size was always higher in pumice (range 492–1844 μm) than in biochar (range 19–22 μm) (Table 2).

In the pumice, the mean relative proportion of pores in each pore size group out of the total pore volume followed the order ultra-micropore > micropore > mesopore > macropore, irrespective of the pumice particle size. All differences were significant at $P < 0.05$. In this material, the proportion of ultra-micropores plus micropores (87%) were more than six-fold that of the mesopores plus macropores (13%), reflecting that pumice mainly consists of pores <30 μm (Fig. 1*a*). Similar patterns of pore-size distribution were observed for biochar but the mean relative proportion of ultra-micropores plus micropores (95%) was significantly greater ($P < 0.05$) than those of pumice (87%). The relative proportion of micropores, which are those responsible for the retention of plant-available water, was significantly smaller ($P < 0.05$) in biochar (31%) than in pumice (41%), irrespective of their particle size. The relative proportion of mesopores plus macropores in pumice increased from Pu-1.5 (8%) to Pu-3 (12%) to Pu-6 (19%). All differences were significant at $P < 0.05$. There was no particle size effect in the pore size distribution of biochar (Fig. 1*a*, *b*).

Values of total SEM porosity in pumice were found to be significantly smaller ($P < 0.05$) in Pu-6 (58.5%) than in Pu-1.5 (65.6%). Differences in the absolute porosity, namely the volume of pores out of total volume of amendment, in the different pore size groups considered of the three pumice particle sizes were significantly different ($P < 0.05$). The highest values for both ultramicro- and micro-scale porosity were found in Pu-1.5 (32.7 and 27.2%), followed by Pu-3 (28.3 and 24.9%), and then Pu-6 (25.0 and 22.7%). An opposite pattern was observed in both meso- and macro-scale porosity with the lowest being under Pu-1.5 (3.5 and 2.1%), followed by Pu-3 (5.1 and 2.6%), and the highest in Pu-6 (6.4 and 4.5%) (Fig. 1*c*).

For biochar, the absolute porosity in different pore size groups followed the order ultramicro- (44.2%) > micropore (20.7%) > mesopore (1.8%), and > macropore-scale porosity (1.1%), irrespective of the biochar particle size. Absolute porosity in the different pore size groups of biochar varied narrowly between the three particle sizes, with the most relevant difference found in the 3-cm biochar particle size, which had a significantly greater ($P < 0.05$) ultramicro-scale porosity than the 6-cm biochar. The opposite pattern was observed for micropore, mesopore and macropore-scale porosity (Fig. 1*d*).

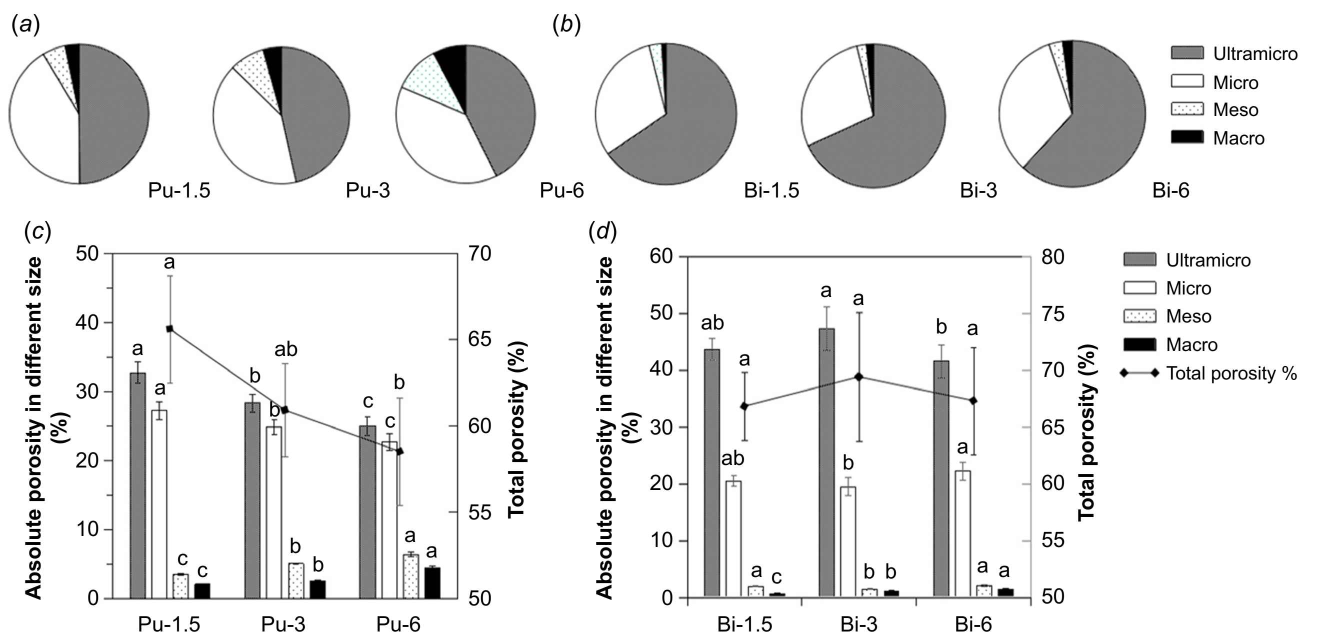

Fig. 1. The mean relative proportion of pores in each pore size group out of total pore volume in (*a*) pumice and (*b*) biochar ($n = 6$). Mean values of pumice pore parameters (absolute porosity for each pore size group out of total volume of the amendment and total porosity) in (*c*) pumice and (*d*) biochar ($n = 6$). Ultramicropores represent vesicles with Ø smaller than 3 μm; micropores represent vesicles with Ø of 3–30 μm; mesopores represent vesicles with Ø of 30–100 μm; macropores represent vesicles with Ø larger than 100 μm. Pu-1.5, pumice with 1.5-cm Ø; Pu-3, pumice with 3-cm Ø; Pu-6, pumice with 6-cm Ø; Bi-1.5, biochar with 1.5-cm Ø; Bi-3, biochar with 3-cm Ø; Bi-6, biochar with 6-cm Ø. Data were analysed by Kruskal–Wallis and Nemenyi tests using the SPSS version 14.0 software package (IBM, Armonk, New York, USA). Different letters in the same colour block indicate significant differences between the treatments ($P < 0.05$).

Mobile water fraction (θ_m) in pumice and biochar

The θ_m of the pumice- and biochar-amended sandy soil, when subsequently leached, was estimated based on the Na^+ concentration at the end of the experiment, relative to the amount added (C^*/C_m) (Fig. 2). It should be noted that the amount of water-soluble Na^+ in the amendments before the experiment was <0.05 mg cm^{-3}, and no significant differences between particle sizes were observed in either the pumice or the biochar (Table 1). When averaging C^*/C_m from the treatments grouped by pumice particle size, there was an increase in the mobile water fraction (from 0.14 to 0.24) with increasing particle size of pumice. The differences between treatments were significant at $P < 0.05$, except between Pu-1.5 and Pu-3. When averaging the relative Na^+ concentration from the treatments grouped by the pumice application rate, no significant differences were observed between the three application rates.

With biochar, when averaging the relative Na^+ concentration from the different treatments grouped by biochar particle size, the mobile water fraction showed a small decrease with an increasing particle size (from 0.085 to 0.080) and was only significant ($P < 0.05$) between Bi-1.5 and Bi-6 treatments. When averaging the relative Na^+ concentration from the treatments grouped by biochar application rate, no significant differences were detected between the three application rates (Fig. 2).

Discussion

Both pumice and biochar contributed to water retention and dilution of salinity when applied to a sandy soil

Porosity in terms of pore size and pore distribution greatly influence soil properties, particularly aeration, drainage and water retention (Klug and Cashman 1996). The wide pore size range observed in the pumice under study is consistent

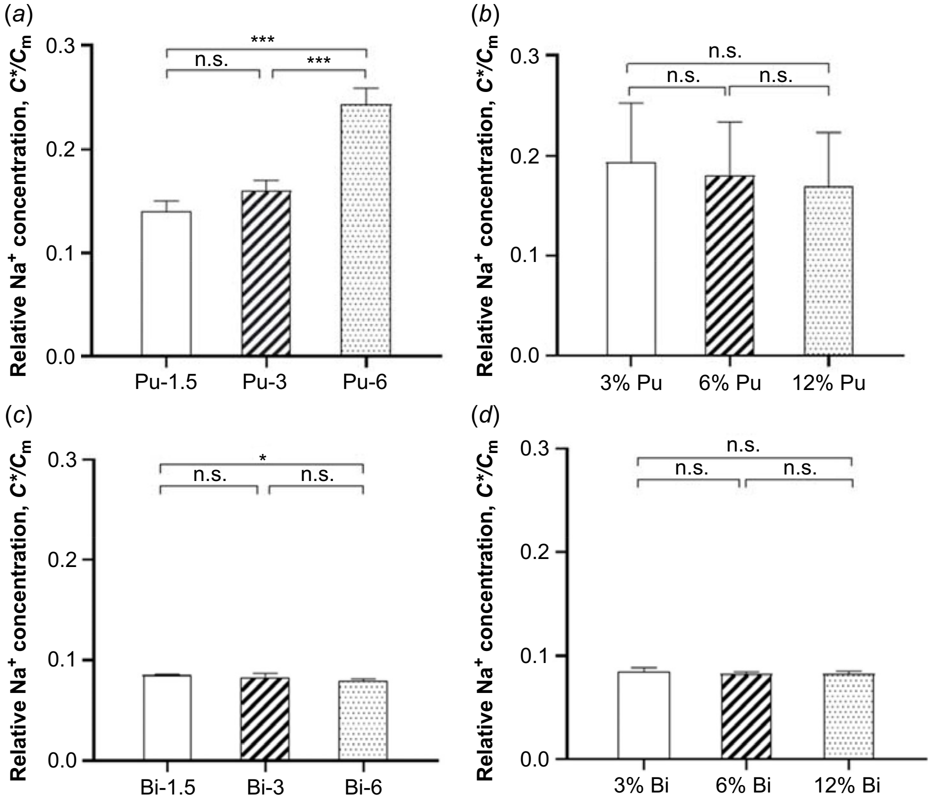

Fig. 2. The relative Na^+ concentration of pumice and biochar at the end of the experiment. Bar charts showing: (*a*) when averaging the relative Na^+ from the treatments grouped by pumice particle size (1.5-, 3-, and 6-cm), (*b*) when averaging the relative Na^+ from the treatments grouped by pumice application rates (3%, 6%, and 12%, v/v, basis), (*c*) when averaging the relative Na^+ from the treatments grouped by biochar particle size (1.5-, 3-, and 6-cm), (*d*) when averaging the relative Na^+ from the treatments grouped by biochar application rates (3%, 6%, and 12%, v/v, basis). Data were analysed by one-way ANOVA using Graph pad prism 8 software and expressed as mean ± s.d. * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$. Differences were considered significant if $P < 0.05$.

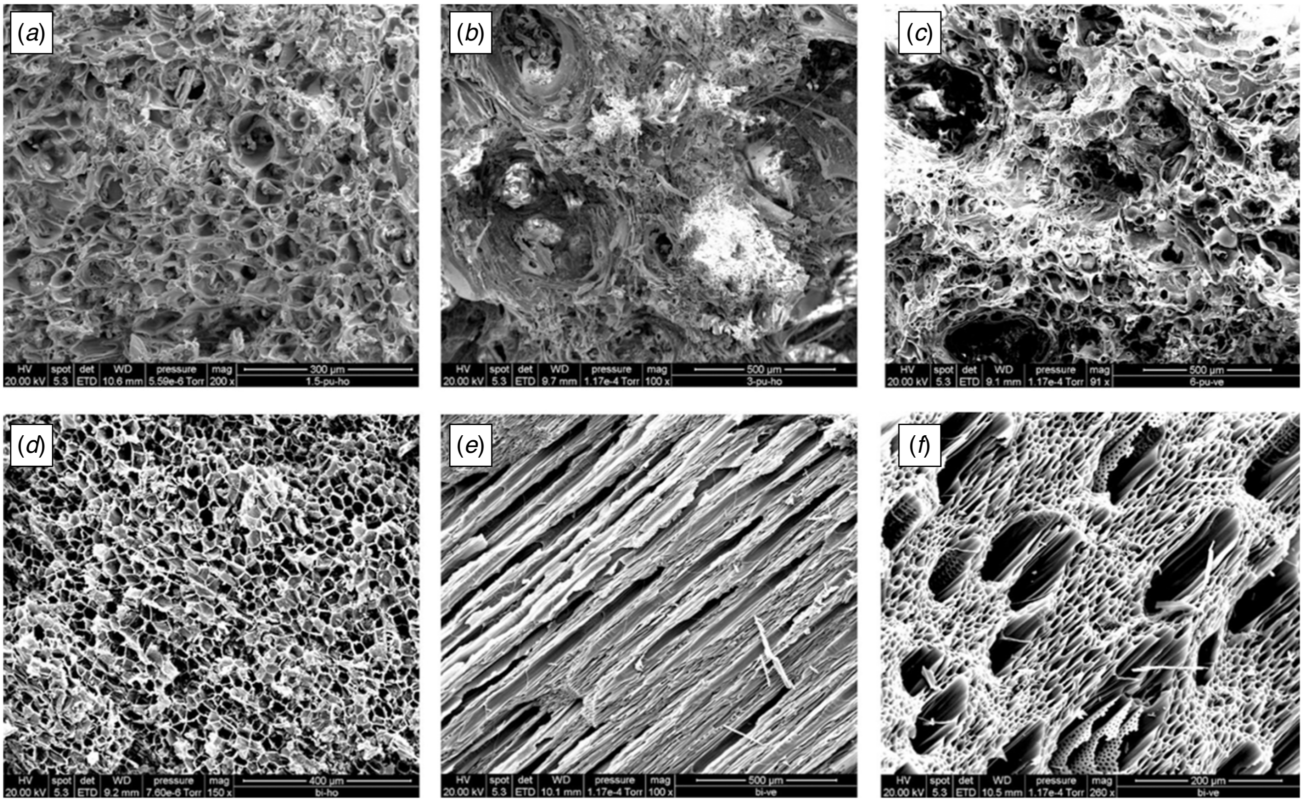

Fig. 3. Representative SEM images of the studied pumice and biochar. Images showing (*a*) pumice with 1.5-cm Ø, (*b*) pumice with 3-cm Ø, (*c*) pumice with 6-cm Ø, (*d*) biochar with 1.5-cm Ø, (*e*) biochar with 3-cm Ø, (*f*) biochar with 6-cm Ø.

with the observations of Ersoy *et al.* (2010) working with pumice (of particle size ranging between 0.5- and 4-cm Ø) from the Tatvan region of Turkey. This large variety of pore sizes is been attributed to the rapid release of pressure during volcanic eruptions, which leads to gas expansion and the formation of multiple bubbles (Whitham and Sparks 1986). The elongation of micropores occurs due to the ductile elongation in the volcanic conduit (Fig. 3*a–c*) or in the case of pumiceous lavas, during flow (Papadopoulos *et al.* 2008). Particle size of the pumice had an influence in the size of those pores, where the average pore size of Pu-6 (1.8 mm) was significantly higher than that of Pu-1.5 (0.5 mm). This is likely attributed to the differences in total volatile content of the magmas between the different particle size pumice. More volatiles and faster ascent results in more and larger vesicles (Mitchell *et al.* 2019). Our pumice samples were taken from the Tongariro National Park and originated from the 1994–1995 Mount Ruapehu eruption. This had a predominance of ultra-micropores (<3 μm) and micropores (3–30 μm), under the three given particle sizes. This is probably associated to the rapid release of gas as a result of a large explosive force during the eruption (Pardo *et al.* 2012). These findings agree with a study of von Lichtan *et al.* (2016) who found the SEM-observed peak in vesicle abundance at 25 μm in all pumice samples taken from the most recent eruption (1.8 ka) of the Taupo Volcano (New Zealand).

Total porosity of pumice, as estimated from segmented areas of pixels (ranging from 58.5 to 65.6%), was larger than that estimated by von Lichtan *et al.* (2016) using the mercury intrusion porosimetry in pumice from the nearby region (Taupo 1.8 ka eruption) (ranging from 41.9 to 53.8%). The reason for this difference is probably the distinct geological formation conditions, as well as the different methods used for their measurement (Lubda *et al.* 2005; Ersoy *et al.* 2010).

The greater micro-scale porosity and the smaller macro-scale porosity in 1.5-cm Ø pumice is consistent with the results from the mobile water fraction analyses. These showed that when compared to pumice of large particle sizes, smaller particle-sized pumice had a smaller volume of mobile water, due to its larger water holding porosity (microporosity) and larger hydraulic conductivity (Raviv *et al.* 2002) than the coarser pumice. However, pumice of large particle size (e.g. 6-cm) had a larger volume of air-filled porosity compared with the smaller particle sizes studied, and this may contribute to soil aeration (Raviv *et al.* 2002). Considering that pores >100 μm drain easily, and those between 3 and 30 μm retain plant-available water (Landis *et al.* 1990), the pumice of all particle sizes under study could suit as amendment to enhance the permeability of clayey soils, as well as to improve the water holding capacity of sandy soils.

The larger relative proportion of pores able to retain plant-available water (41 vs 31%) of pumice at a similar total porosity than that of the specific biochar under study (Fig. 1*a*, *b*) suggests that this pumice may perform better on improving plant-available water retention capacity, compared with this biochar produced from willow at a highest heating temperature of 350°C. Additionally, it should be noted the properties of pumice and biochar differ in other aspects, such as the fact that biochar has been promoted as a technology to sequester carbon, for provision of nutrients, and as a liming material (Camps-Arbestain *et al.* 2015). Therefore, the selection of one material, or the other, should be based on the desired impact.

Pumice was shown to be better at contributing to water mobility than biochar under near-saturated conditions

The mobile water fraction study supports the pattern that is commonly observed in pumice- and biochar-amended soils, with a larger soil moisture content where these amendments have been applied, as compared with the unamended soils (Downie *et al.* 2009; Malekian *et al.* 2012; Burrell *et al.* 2016). This characteristic has commonly been attributed to the porous nature of these materials and, in particular, to their small 'mean' pore size (Clothier *et al.* 1995; Sahin *et al.* 2005). In fact, in this study, the fraction of immobile water of pumice was nearly four-fold that of mobile water (0.82 vs 0.18), and this ratio was 11-fold in biochar (0.92 vs 0.08). A higher mobile water fraction in a larger particle sized pumice agrees with its larger proportion of macro-scale and meso-scale porosity. Thus, the application of these two materials could contribute to alleviate salt and plant-water stress by retaining more water and diluting salt concentration in the soil solution under arid conditions, when a biochar with a small ash fraction is used.

The fact that there were no obvious differences in the mobile water fraction between the three particle sizes biochar under study could be explained by the fact that they originated from the same biochar, which was crushed before the particle screening, and the overall small contribution of biochar to the water mobility. Furthermore, in a previous study carried out with the same pumice and biochar (Kong *et al.* 2021), accumulation of Na^+ within biochar was one fifth that of pumice (70 vs 380 meq L^{-1}) reflecting the lower ability of biochar to retain Na^+. Here, we only considered the effect of porosity and pore size distribution on the mobile water fraction of pumice and biochar. Other aspects such as the influence of differences in pore morphology characteristics, homogeneity of pores and pore sizes, and the connectivity of the pore structure (Sahin *et al.* 2005; Ersoy *et al.* 2010; Fauria *et al.* 2017; Liu *et al.* 2017) cannot be discarded. But these were not investigated in this study and deserve further research.

Conclusions

The findings of our study have offered an insight into the relationship between the physical properties of the porosity and pore size distribution of a pumice and a biochar and the fraction of mobile–immobile water present in these materials when added to a sandy soil. The results emphasise a predominance of pores with Ø < 30 μm and relatively high total porosity under the three given particle sizes of both materials, which are expected to contribute to water retention when these amendments are used in sandy soil, and to the dilution of salinity in salt-affected sandy soils assuming a low ash biochar is used. The overall larger contribution of pumice to the water mobility than that of biochar under near-saturated conditions could be related to its relatively higher levels of macro-scale plus meso-scale porosity, and this increased as the pumice particle size increased. The knowledge generated in this study provides an enhanced understanding of the relationship between the pore characteristics and mobile water fractions of pumice and biochar, and their implications for potential use in saline environments. In future studies, Nuclear Magnetic Resonance (NMR) technology could also be used as this has been proven to be a non-destructive tool for characterisation of the pore size distribution of porous samples (de Pierri *et al.* 2022). The application of this technique might help further validate the results from our study.

Supplementary material

Supplementary material is available online.

References

Abou-Baker N, El-Dardiry E (2016) 'Integrated management of salt affected soils in agriculture'. (Elsevier Science and Technology)

Alon BG, Alon T, Noemi TZ (2006) The sustainability of arid agriculture: trends and challenges. *Annals of Arid Zone* **45**, 227–258.

Batista EMCC, Shultz J, Matos TTS, Fornari MR, Ferreira TM, Szpoganicz B, de Freitas RA, Mangrich AS (2018) Effect of surface and porosity of biochar on water holding capacity aiming indirectly at preservation of the Amazon biome. *Scientific Report* **8**, 10677. doi:10.1038/s41598-018-28794-z

Brewer CE, Chuang VJ, Masiello CA, Gonnermann H, Gao X, Dugan B, Driver LE, Panzacchi P, Zygourakis K, Davies CA (2014) New approaches to measuring biochar density and porosity. *Biomass and Bioenergy* **66**, 176–185. doi:10.1016/j.biombioe.2014.03.059

Burrell LD, Zehetner F, Rampazzo N, Wimmer B, Soja G (2016) Long-term effects of biochar on soil physical properties. *Geoderma* **282**, 96–102. doi:10.1016/j.geoderma.2016.07.019

Camps-Arbestain M, Amonette JE, Singh B, Wang T, Schmidt HP (2015) A biochar classification system and associated test methods. In 'Biochar environmental management'. 2nd edn. (Eds J Lehmann, J Joseph) pp. 165–193. (Science and Technology and Implementation, Earthscan: London)

Cekova B, Pavlovski B, Spasev D, Reka A (2013) Structural examinations of natural raw materials pumice and trepel from Republic of Macedonia. In 'Proceedings of the XV Balkan mineral processing congress, Sozopol, Bulgaria, 12–16 June'. pp. 73–75.

Claridge GGC (1961) Mineralogy and origin of the yellow-brown sands and related soils. *New Zealand Journal of Geology and Geophysics* **4**, 48–72. doi:10.1080/00288306.1961.10420138

Clothier BE, Kirkham MB, McLean JE (1992) In situ measurement of the effective transport volume for solute moving through soil. *Soil Science Society of America Journal* **56**, 733–736. doi:10.2136/sssaj1992.03615995005600030010x

Clothier BE, Heng L, Magesan GN, Vogeler I (1995) The measured mobile-water content of an unsaturated soil as a function of hydraulic regime. *Australian Journal of Soil Research* **33**, 397–414. doi:10.1071/SR9950397

de Pierri L, Novotny EH, Cerri CEP, de Souza AJ, Mattos BB, Tornisielo VL, Regitano JB (2022) Accessing biochar's porosity using a new low field NMR approach and its impacts on the retention of highly mobile herbicides. *Chemosphere* **287**, 132237. doi:10.1016/j.chemosphere.2021.132237

Downie A, Crosky A, Munroe P (2009) Physical properties of biochar. In 'Biochar for environmental management: science and technology'. (Eds J Lehmann, S Joseph) pp. 13–32. (Earthscan: London)

Drzal MS, Cassel DK, Fonteno WC (1999) Pore fraction analysis: a new tool for substrate testing. *Acta Horticulturae* **481**, 43–54. doi:10.17660/ActaHortic.1999.481.1

Ersoy B, Sariisik A, Dikmen S, Sariisik G (2010) Characterization of acidic pumice and determination of its electrokinetic properties in water. *Powder Technology* **197**, 129–135. doi:10.1016/j.powtec.2009.09.005

Fauria KE, Manga M, Wei Z (2017) Trapped bubbles keep pumice afloat and gas diffusion makes pumice sink. *Earth and Planetary Science Letters* **460**, 50–59. doi:10.1016/j.epsl.2016.11.055

Herath HMSK, Camps-Arbestain M, Hedley M (2013) Effect of biochar on soil physical properties in two contrasting soils: an Alfisol and an Andisol. *Geoderma* **209–210**, 188–197. doi:10.1016/j.geoderma.2013.06.016

Impoco G, Carrato S, Caccamo M, Tuminello L, Licitra G (2006) Quantitative analysis of cheese microstructure using SEM imagery. In 'Image analysis methods for industrial applications: SIMAI 2006 Minisymposium, Baia Samuele (RG), Italy'.

Kong C, Camps-Arbestain M, Clothier B, Bishop P, Vázquez FM (2021) Use of either pumice or willow-based biochar amendments to decrease soil salinity under arid conditions. *Environmental Technology & Innovation* **24**, 101849. doi:10.1016/j.eti.2021.101849

Klug C, Cashman KV (1996) Permeability development in vesiculating magmas: implications for fragmentation. *Bulletin of Volcanology* **58**, 87–100. doi:10.1007/s004450050128

Landis TD, Tinus RW, McDonald SE, Barnett JP (1990) Growing media. In 'The container tree nursery manual. Volume 2. Containers and growing media'. pp. 41–85. (USDA Forest Service: Washington, DC)

Liu Z, Dugan B, Masiello CA, Gonnermann HM (2017) Biochar particle size, shape, and porosity act together to influence soil water properties. *PLoS ONE* **12**, e0179079. doi:10.1371/journal.pone.0179079

Lubda D, Lindner W, Quaglia M, von Hohenesche CF, Unger KK (2005) Comprehensive pore structure characterization of silica monoliths with controlled mesopore size and macropore size by nitrogen sorption, mercury porosimetry, transmission electron microscopy and inverse size exclusion chromatography. *Journal of Chromatography A* **1083**, 14–22. doi:10.1016/j.chroma.2005.05.033

Lura P, Bentz DP, Lange DA, Kovler K, Bentur A (2004) Pumice aggregates for internal water curing. In 'International RILEM symposium on concrete science and engineering – a tribute to Arnon Bentur'. (Eds K Kovler, J Marchand, S Mindess, J Weiss) pp. 137–151. (National Institute of Standards and Technology) Available at https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=860543

Malekian A, Valizadeh E, Dastoori M, Samadi S, Bayat V (2012) Soil water retention and maize (*Zea mays* L.) growth as effected by different amounts of pumice. *Australian Journal of Crop Science* **6**, 450–454.

Mitchell SJ, Houghton BF, Carey RJ, Manga M, Fauria KE, Jones MR, Soule SA, Conway CE, Wei Z, Giachetti T (2019) Submarine giant pumice: a window into the shallow conduit dynamics of a recent silicic eruption. *Bulletin of Volcanology* **81**, 42. doi:10.1007/s00445-019-1298-5

Noland DA, Spomer LA, Williams DJ (1992) Evaluation of pumice as a perlite substitute for container soil physical amendment. *Communications in Soil Science and Plant Analysis* **23**, 1533–1547. doi:10.1080/00103629209368685

Papadopoulos AP, Bartal A, Silber A, Saha UK, Raviv M (2008) Inorganic and synthetic organic components of soilless culture and potting mixes. In 'Soilless culture: theory and practice'. (Eds M Raviv, JH Lieth) pp. 505–543. (Academic Press: San Diego) doi:10.1016/B978-044452975-6.50014-9

Pardo N, Cronin S, Palmer A, Procter J, Smith I (2012) Andesitic Plinian eruptions at Mt. Ruapehu: quantifying the uppermost limits of eruptive parameters. *Bulletin of Volcanology* **74**, 1161–1185. doi:10.1007/s00445-012-0588-y

Rajkovich S, Enders A, Hanley K, Hyland C, Zimmerman AR, Lehmann J (2012) Corn growth and nitrogen nutrition after additions of biochars with varying properties to a temperate soil. *Biology and Fertility of Soils* **48**, 271–284. doi:10.1007/s00374-011-0624-7

Rasa K, Heikkinen J, Hannula M, Arstila K, Kulju S, Hyväluoma J (2018) How and why does willow biochar increase a clay soil water retention capacity? *Biomass and Bioenergy* **119**, 346–353. doi:10.1016/j.biombioe.2018.10.004

Raviv M, Wallach R, Silber A, Bar-Tal A (2002) Substrates and their analysis. In 'Hydroponic production of vegetables and ornamentals'. (Eds D Savvas, HC Passam) pp. 25–101. (Embryo Publications: Athens)

Sahin U, Ors S, Ercisli S, Anapali O, Esitken A (2005) Effect of pumice amendment on physical soil properties and strawberry plant growth. *Journal of Central European Agriculture* **6**, 361–366.

Saifullah, Dahlawi S, Naeem A, Rengel Z, Naidu R (2018) Biochar application for the remediation of salt-affected soils: challenges and opportunities. *Science of The Total Environment* **625**, 320–335. doi:10.1016/j.scitotenv.2017.12.257

von Lichtan IJ, White JDL, Manville V, Ohneiser C (2016) Giant rafted pumice blocks from the most recent eruption of Taupo volcano, New Zealand: insights from palaeomagnetic and textural data. *Journal of Volcanology and Geothermal Research* **318**, 73–88. doi:10.1016/j.jvolgeores.2016.04.003

Waldron KW (2014) 'Advances in biorefineries: biomass and waste supply chain exploitation'. (Woodhead: London)

Whitham AG, Sparks RSJ (1986) Pumice. *Bulletin of Volcanology* **48**, 209–223. doi:10.1007/BF01087675

Data availability. The data that support this study will be shared upon reasonable request to the corresponding author.

Conflicts of interest. The authors declare no conflicts of interest.

Declaration of funding. The authors acknowledge the China Scholarship Council for facilitating and supporting this research.

Acknowledgements. The authors acknowledge Stanislav A. Garbuz from Massey University for helping in the supply of biochar.

Author affiliations

[A]School of Agriculture and Environment, Massey University, Private Bag 11222, Palmerston North 4442, New Zealand.

[B]Plant and Food Research, Palmerston North 4442, New Zealand.