RESEARCH PAPER

Exploring efficiency of biochar in enhancing water retention in soils with varying grain size distributions using ANN technique

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Abstract

Recently, incentives have been provided in many countries, including Canada and Denmark, to produce biochar for construction usage. This is done because biochar is carbon negative and can help achieve the emission reduction goal of 2030. This technical note aims to analyse the efficiency of biochar in soils with varying grain size distributions for enhancing soil–water characteristic curve (SWCC). The combinations of biochar content and grain size distributions corresponding to the maximum and minimum efficiencies were explored. Artificial neural network-based model for predicting SWCC as a function of soil suction and grain size distribution was developed. A new factor (the ratio of fine (silt + clay) and coarse (sand) content) was proposed for the interpretation of the efficiency of biochar in soils. The newly developed model is able to predict SWCC reasonably well. Biochar amendment is found to influence both dry and wet sides of soils with a clay content lower than threshold content (6–8%). Beyond threshold content, the influence of biochar appears to reduce. However, in the case of high sand content soils (90%), the normalized water content value on the drier side is generally higher as compared to soils with lower sand content. Based on the sensitivity analysis, it was found that the ratio of fine to sand content is the most influential, while biochar content is the least influential.

Keywords Artificial neural network · Biochar · Ratio · Soil suction · Soil–water characteristic curve

Abbreviations

ANN	Artificial neural network
BAS	Biochar amended soils
MAPD	Mean absolute percentage deviation
NWC	Normalized water content
PAW	Plant available water
PWP	Permanent wilting point
R^2	Coefficient of determination
SWCC	Soil–water characteristic curve
WRC	Water retention capacity

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1 Introduction

The biochar addition generally increases the water retention capacity of soils, which can be attributed to the biochar's high porosity and hydrophilic nature [16, 61, 74]. In addition, biochar has many other promising properties like carbon sequestration and high plant nutrient value [10, 25, 35, 45, 46, 48, 62, 65, 66, 76]. This enhancement mainly depends on the type of the feedstock of biochar, the type of soil and the soil–biochar mixture rates. It is necessary to understand the water retention mechanism of biochar amended soils (BASs) to promote biochar as a soil amendment [69]. Sufficient literature is available, which shows that the water retention capacity (WRC) of the biochar soil composite is increased compared to bare soil [22, 42]. Mollinedo et al. [40] observed that the fine-sized

biochar particles change the soil pore arrangement and increase surface area, void ratio and WRC of soil–biochar composite. On applying biochar to soil, the WRC of soil (medium-textured boreal agriculture soil) increased by 11% [29] and 32% [8] in sandy loam soil. Gopal et al. [20] observed a reduction in infiltration rate and an enhancement in WRC with an increase in biochar amendment. Similarly, Garg et al. [18] observed that the addition of biochar increased the water retention capacity of unsaturated soils (loam and sandy loam). The study also demonstrated that the addition of biochar modified the soil–water characteristic curve.

Porosity, void ratio and soil structure get altered by biochar addition, specifically depending upon the particle shape, size and internal structure of biochar [67]. The internal structure of biochar particles determines their WRC and shape (elongated/oval/spherical), and size determines the complexity and density of soil–biochar composite and capillary system [37]. Liu et al. (2017) observed the effect of 2% biochar amendment of three different particle size samples with sand. It was noticed that the saturation water content, field capacity, permanent wilting point (PWP) and plant available water (PAW) in soil–water characteristic curve (SWCC) increased when compared with the other two samples: sand − fine sand and sand + coarse sand (replacing biochar with fine sand and coarse sand). The authors concluded that more porous and irregular shaped biochar particles are more effective in increasing water retention of sandy soils [37, 47, 49, 68]. Duarte et al. [26] modified eight samples with agricultural residue biochar of size > 2 mm, 2–0.15 mm and < 0.15 mm with 200 g soils (loamy and sandy) at 0.92 g of biochar (∼ 25 Mg/hec). After allowing an incubation period of 1 year, it was noticed that biochar particle size of < 0.15 mm is most suitable for increasing water retention in the soils (particularly loamy soil). It was observed that soil's physical properties were dependent upon the particle size of biochar. Similarly, in another study conducted by Alghamdi et al. [3], fine biochar particles < 0.1 mm increased the water content at field capacity and available water content more than that of particle size greater than 0.1 mm, probably due to increased surface area, microporosity and biochar's porous structure in light-textured soils after an incubation period of 120 days.

Though many studies reported an increase in WRC, there are some studies where the effect of biochar has been either negligible or negative. Some authors observed both increase and decrease [23, 36, 43, 64], some reported increase only [1], whereas some reported no effect [25]. Bordoloi et al. [7] observed an increase in WRC of silty sandy soil, while Hardie et al. [21] observed no noticeable effect of biochar on drainable porosity, field capacity, PWP, PAW content or soil moisture content of a sandy,

loamy soil. Further, the effect of biochar on WRC may vary with the type of feedstock, from which biochar was produced [31, 61]. Biochars produced from plant feedstock types tend to have a higher porosity than that of animal feedstock [13, 30, 31]. As far as authors are aware, there is a lack of systematic study that investigates the extent of biochar effect on WRC of soils with varying grain size distributions. It is difficult to interpret the extent or efficiency of biochar on WRC of soils from literature due to high variability in testing conditions such as instrumentation, climate and type of biochar.

There are several numerical techniques to model material behaviour effectively in different disciplines [17, 24, 32, 34, 54, 55]. One of such techniques, artificial neural network (ANN), has proven to be an effective approach for analysing material behaviour from limited experimental results [16, 33, 52, 61, 63]. Many studies have reported using the ANN to study soil properties [2, 9]. ANNs are based on a learning technique that imitates the biological learning process occurring in the brain and presents a robust way to predict responses from a dataset [12, 53]. Vasu et al. [57] used ANN to estimate soil–water characteristic curve (SWCC) for Korea's weathered soil using the Fredlund and Xing equation. Zainal and Fadhil [70] determined SWCC by ANN using properties like air entry point and residual degree of saturation. Similarly, Johari and Hooshmand [27] used gene expression programming to predict SWCC. Johari and Javadi [28] used clay and silt contents along with void ratio, gravitational water content and suction and estimated SWCC using the ANN technique. Hence, ANN technique can serve as an important tool for developing models and analysing soil behaviour.

This study aims to investigate the efficiency of biochar in affecting the WRC of soils with varying grain size distributions. Database of SWCCs of soils with and without biochar amendment was systematically established. ANN models were developed based on an established data set. Models were developed as a function of parameters such as percentages of biochar amendment, clay, sand and a new factor (the ratio of fine (silt + clay) and coarse (sand) content).

2 Materials and methodology

2.1 Test procedure

Measured data collected from the studies [6, 14, 15, 41, 43, 65] are used in this study. Soils from these studies varied from sandy to silty clay and pure clay. Sand content, clay content and silt content vary from 58 to 98%, 0 to 20% and 2 to 37%, respectively. Biochar

amendment varies from 0 to 15%. Biochars were obtained from different feedstock types such as water hyacinth, peanut shell and dairy manure. Detail of biochar type and production was given in one of the studies [6]. The biomass had a lignocellulosic nature with 46% cellulose content and 21% hemicellulose. The procedure prescribed by Gogoi et al. [19] was adopted for the production of biochar. The biomass was cut into small pieces of 30–50 mm. The temperature of the pyrolysis process was maintained at 300–500 °C for 45 min as per the optimum conditions for water hyacinth species [39]. The biochar produced was cut using an automatic crusher and sieved through a 2-mm sieve. After achieving the desired torrefaction temperature required for biochar production, the sample was removed and subjected to further analysis. The procedure for establishing soil–water characteristic curve varies among the above studies. Studies [6, 14, 15] have established SWCCs use simultaneous measurements of volumetric water content and soil matric suction in a 1-D column set-up, which contains compacted soil–biochar composite. Wong et al. [65] utilized the vapour equilibrium technique to measure SWCC of compacted kaolin clay amended with different biochar percentages.

For preparing the dataset for the training of models, the volumetric water content of the soils was normalized with their maximum water content (i.e., to establish normalized water content (NWC). NWC is defined as per the following equation:

$$\text{Normalized water content} = \frac{\text{Volumetric water content}}{\text{Maximum water content}} \tag{1}$$

This is done to minimize any fluctuations in the data caused due to variation in soil types, soil density, instrumentation type, etc. Future studies need to be conducted to establish full-scale SWCCs for various soil types using the same set of instrumentation and testing conditions (i.e., soil density and soil type).

2.2 ANN procedure

Artificial neural network (ANN) is a learning algorithm that implicitly describes the nonlinear and complex relationship between input data and output results [33, 51]. In the present study, the commercially available Statistica, version 12 software, was used. To develop the model, seven input parameters, viz. soil suction, biochar content, sand content, silt content, clay content, fine content (silt and clay) and the ratio of fine content to sand content, were used. Corresponding to these seven parameters, normalized water content was predicted using two hidden layers in the ANN architecture. Figure 1 presents a flowchart that shows a methodology used for the implementation, and Fig. 2

illustrates the three-layer ANN architecture. In addition, sensitivity analysis was conducted using the newly developed ANN model. The sensitivity analysis is usually performed to identify relative significance of any parameter, which is simply the importance values of each input parameter divided by the largest importance value of the highest contributing parameter. The relative significance of any parameter is expressed as percentage and can be visualized in form of a bar chart. Relative significance values are obtained through the software corresponding to the selected architecture of the neural network, sorted in descending order of importance. This bar chart is a result of comparison of the weights assigned to each input parameter.

3 Results and discussion

## 3.1 Comparison between measured and predicted results

The number of soil samples used in the study was 23. Corresponding to these samples, 794 data points were obtained from the literature. These data points were divided in the ratio of 80:20 for training and testing, respectively. Figure 3 shows a comparison drawn between the measured and the predicted outputs. The SWCC is plotted between normalized water content and soil suction. The proposed model's coefficient of determination (R^2) and mean absolute percentage deviation (MAPD) calculations is conducted using the following equation:

$$\text{MAPD} = \frac{100}{n} \sum_{i=1}^{n} \frac{(M_i - P_i)}{M_i} \tag{2}$$

where M_i = measured value, P_i is the predicted value, and n is the number of observations.

The R^2 value was found to be 0.7109. It is observed that measured and predicted NWC follow a trend, indicating accuracy (in terms of R^2) of the prediction of NWC. The error percentage as calculated by MAPD was reported to be 13.76%.

In order to further visualize the predictive ability of the model, estimated SWCCs for three particular soils at different biochar contents of 0%, 5% and 10% were compared with the measured ones in Fig. 4a–c, respectively. It should be noted that only a few selected plots have been used for comparison. This has been done based on the availability of complete data [6, 14] of grain size distribution and also reported SWCCs at different biochar contents (0%, 5% and 10%). Proportion of sand, silt and clay reported in Bordoloi et al. [6] is 58%, 37% and 5%, respectively. As per Garg et al. [14], proportion of sand, silt and clay is 81.23%, 17%
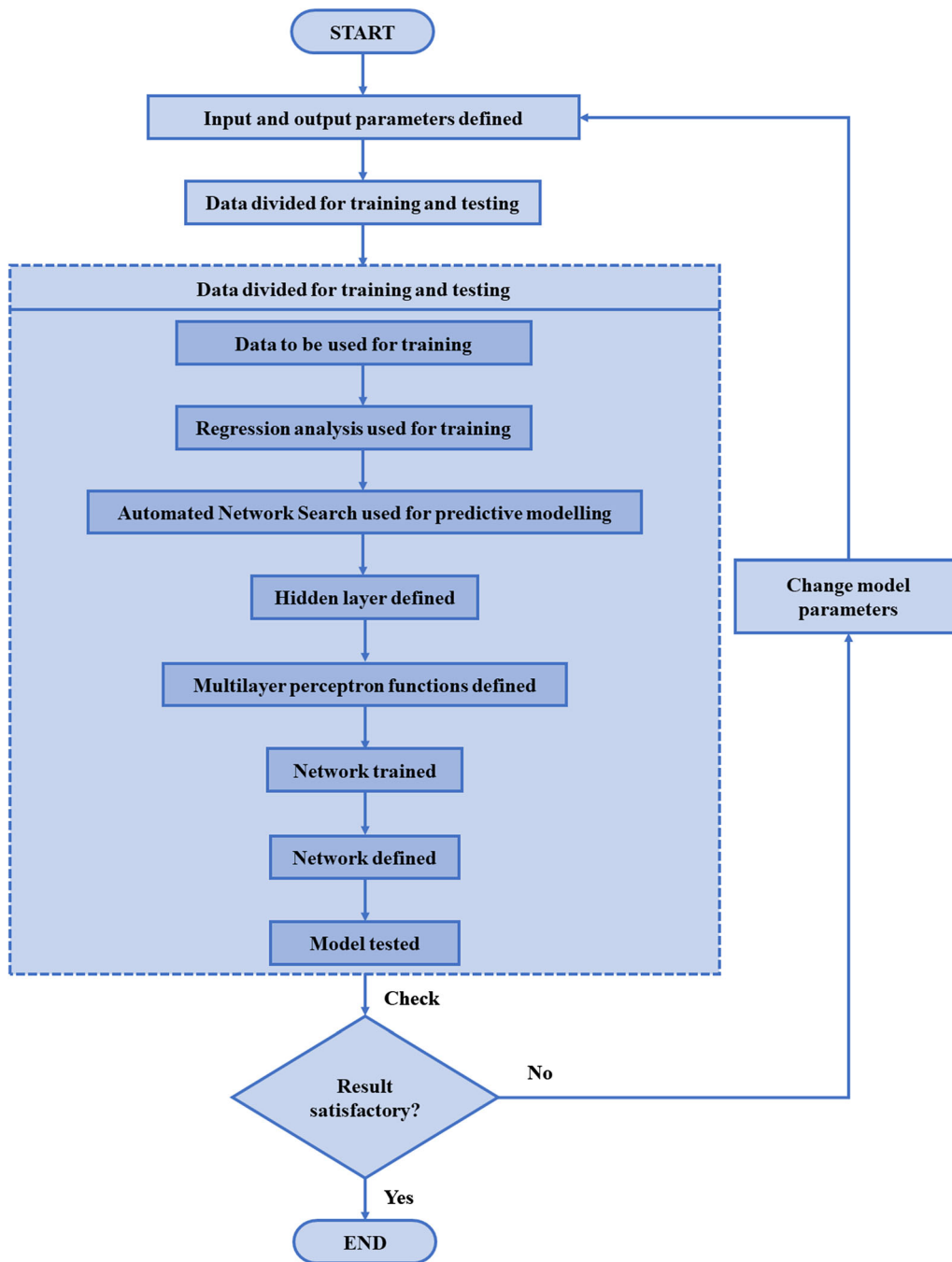
Fig. 1 Flowchart for ANN modelling

and 1.77%, respectively. Soils were compacted at 0.9 times maximum dry density and at optimum moisture content (16.5%) in Bordoloi et al. [6], whereas in Garg et al. [14] soils were compacted at 0.8 times maximum dry density and at optimum moisture content of 18%. In addition to predictions made at similar grain size distributions, additional estimations were made using the developed model to analyse the influence of variation in individual silt, and clay contents. It is evident from the figures that the results

of water content obtained from measured and predicted SWCCs are comparable. It should be noted that there is discrepancy between measured and predicted SWCC values at a higher suction range. Since the ANN model is based on the measured SWRC data, it is reasonable that the prediction may not be able to capture suctions at higher range. This is because of lack of measured SWRC data at higher suctions in most of the studies. As far as authors are aware, only few studies [6, 14, 65] have directly measured
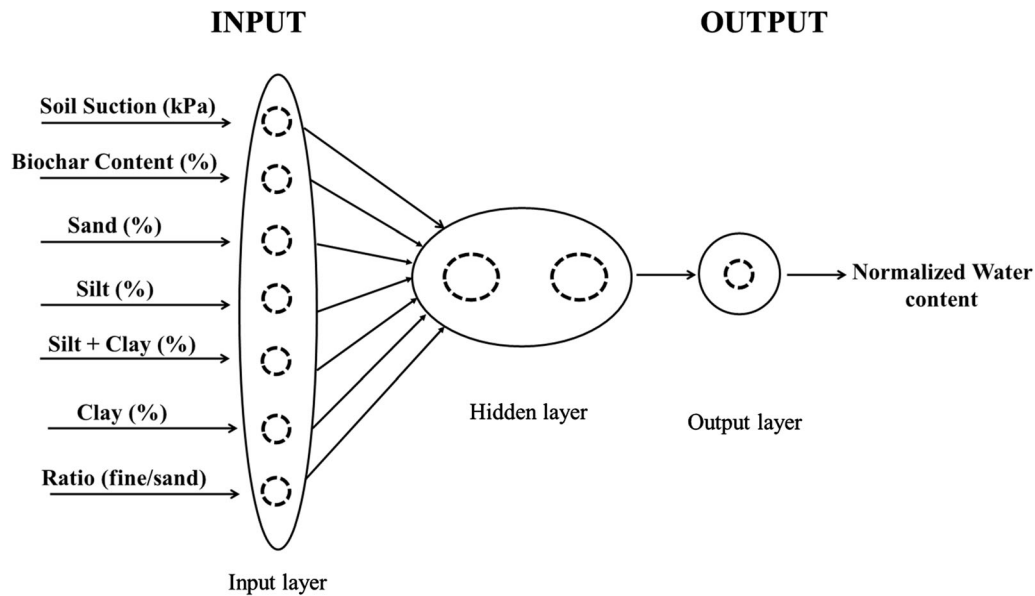
INPUT   **OUTPUT**

Soil Suction (kPa)

Biochar Content (%)

Sand (%)

Silt (%)

Silt + Clay (%)

Clay (%)

Ratio (fine/sand)

Normalized Water content

Hidden layer

Output layer

Input layer

Fig. 2 ANN architecture used for the prediction of normalized water content
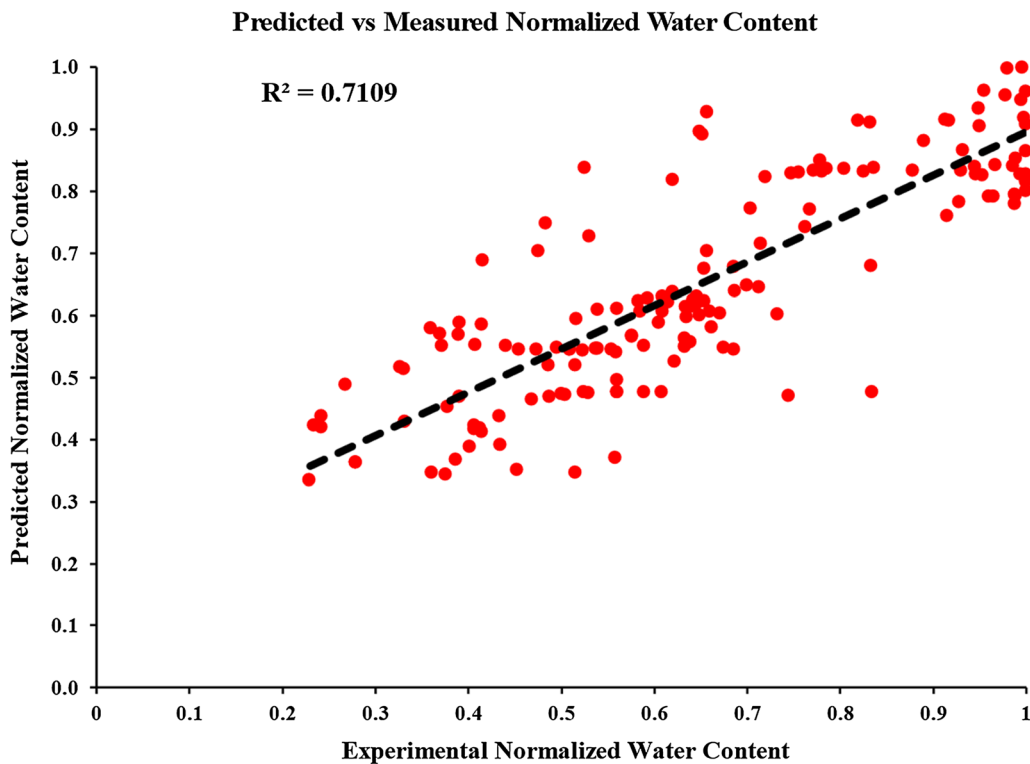
Predicted vs Measured Normalized Water Content

$R^2 = 0.7109$

Fig. 3 Variation between predicted normalized water content and measured normalized water content (R^2)

SWRC for higher suction range. Additionally, the variation in soil suction at higher range could be also caused due to different instrumentation being adopted in studies [38, 44, 71]. Wong et al. [64] adopted humidity-based approach to establish suctions at a higher range, whereas Bordoloi et al. [7] utilized MPS-6 sensor for measuring suction at a higher range. Further systematic studies are needed to measure SWRC for a higher suction range for soils amended with different types of biochars and at varying compaction states.
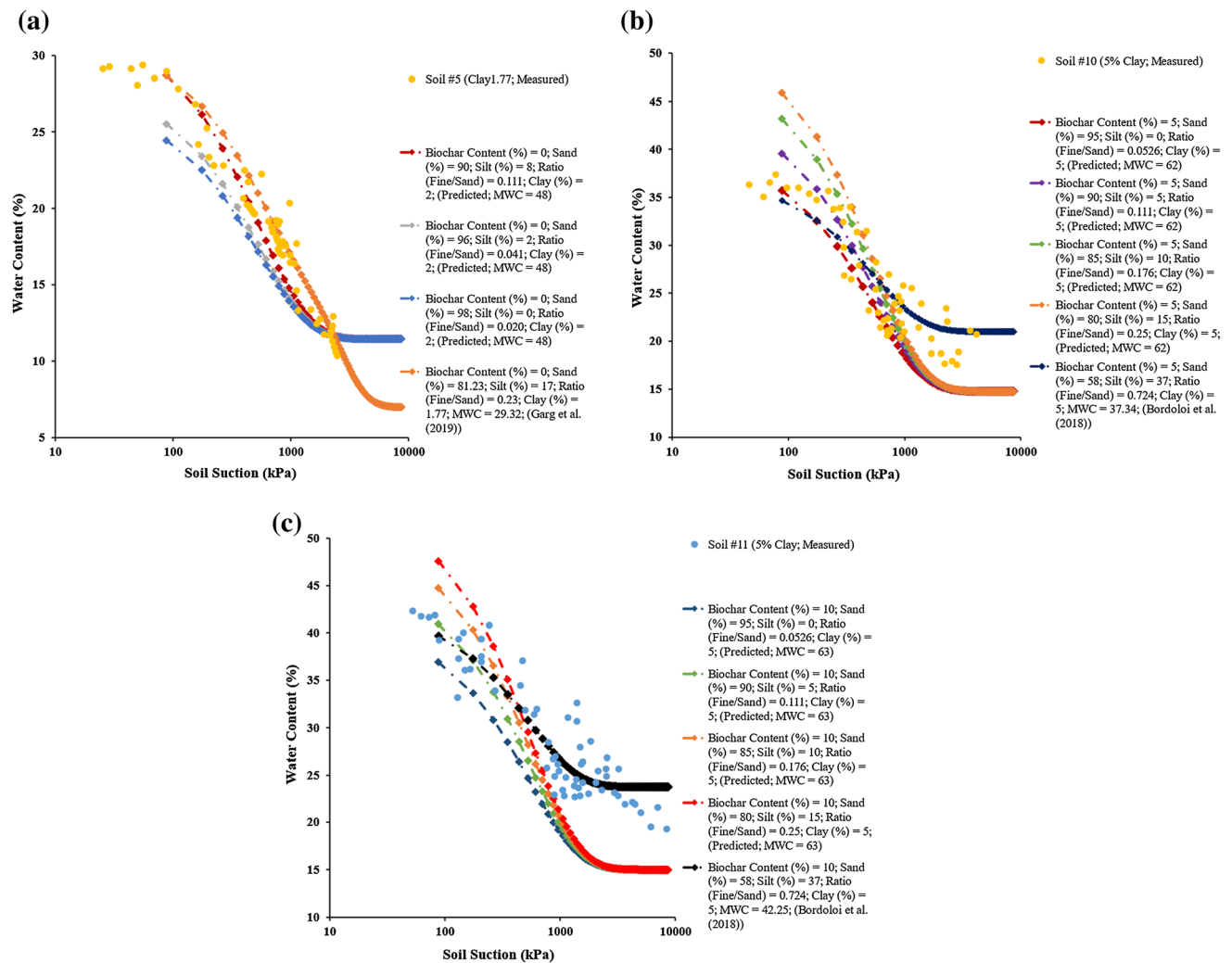
(a)

(b)

(c)

Fig. 4 Comparison of measured and predicted SWCCs corresponding to biochar content of **a** 0%, **b** 5% and **c** 10%

3.2 Influence of clay and silt content on SWCC of soils amended with biochar at different contents

In order to interpret the influence of clay and silt content, prediction of SWCCs was done by systematically varying clay and silt contents. In one case, the silt content was varied from 40 to 30%, while the corresponding clay content varied from 0 to 10%. Sand content is fixed at 60%, while the ratio of fine to coarse content was kept at 0.667. Figure 5a, b shows the biochar effectiveness on SWCCs of soil with different silt and clay contents. Analyses were conducted by keeping the ratio of fine to coarse content (0.667), fine (silt and clay of 40%) and sand content (60%) constant. Clay was varied from 0 to 10%. Correspondingly, silt varied from 40 to 30%. The influence of silt and clay content on SWCCs was analysed for two different biochar percentages (i.e., 3% and 10%), as shown in Fig. 5a, b, respectively.

As observed in Fig. 5a, NWC reduced from 0.9 to 0.65, with an increase in suction for clay contents up to 6%. NWC of 0.65 represents normalized water content corresponding to the drier part of the soil. However, for clay content of 6%, minimum NWC reduced further up to 0.35. At 6% clay content, the change in normalized water content at the wetter side of SWCC is still insignificant. This seems to suggest that with a constant biochar content of 3%, the efficiency (change) of biochar to affect SWCC seems to reduce with an increase in clay content at 6%. The possible reason could be that the amount of smaller size of pores is enhanced with an increase in clay content beyond this optimal amount. Any further addition of finer biochar may not be significant since the existing smaller pores of clay will instead engulf biochar particles. Such pore-filling mechanism effects have also been discussed in the literature (Duarte et al., 2019). For clay content above 8% or above, a significant reduction in NWC is also observed in the wetter side of SWCC. It suggests that for higher clay
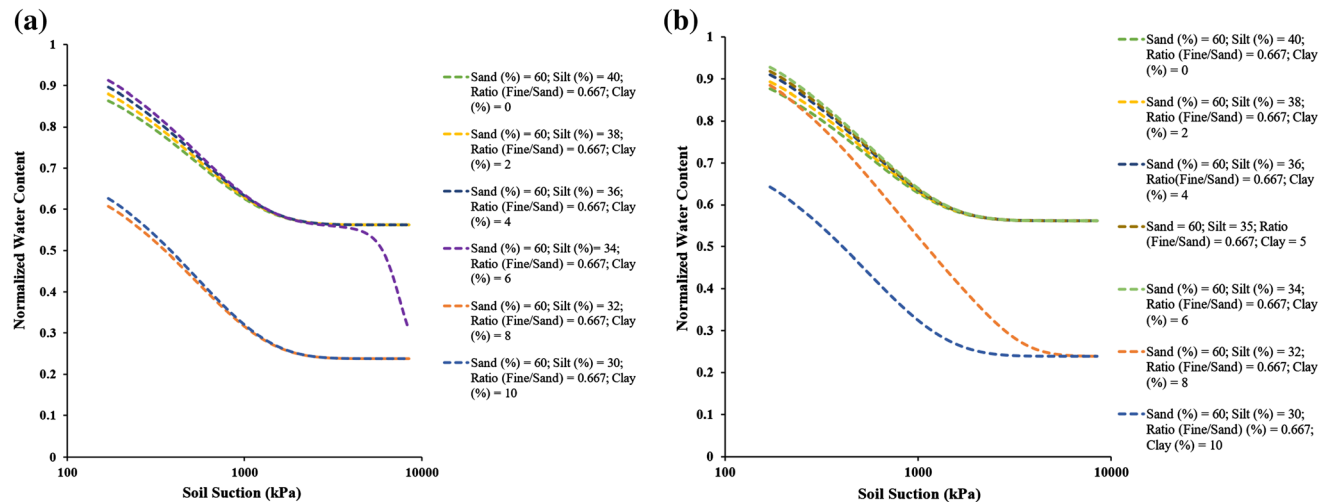
Fig. 5 Variation of normalized water content and soil suction for at different combinations of clay and silt contents for biochar content of **a** 3% and **b** 10%

contents, any effect of biochar may not be significant on the drier or wetter side of SWCC.

The trend of SWCCs for soils at a biochar content of 10% appears to be similar to that of 3%. However, some changes are observed in SWCCs when biochar content is increased to 10%. The threshold clay content beyond which reduction in NWC takes place increased from 6% (biochar content of 3%) to 8% (biochar content of 10%). It also suggests that at the threshold clay content is higher for soils with a larger amount of biochar. The implications of these results suggest that any addition of biochars may not be useful for soils with clay content higher than 6%. This conclusion is obviously dependent on the data used for training of model and prediction. However, this result suggests an important precaution for avoiding the excessive use of biochar in soils with a higher fine content.

In a similar manner, the effect of biochar is likely to be lower in soils compacted at higher densities. Compaction results in a reduction in average pore size. Garg et al. [15] also conducted series of experiments to determine the influence of biochar on water retention in soils compacted at different densities. It was found in their study that biochar was found to be more efficient in soil compacted at 65% followed by 80% compaction as compared to 95%. The pore-filling mechanism of biochar influences WRC and hence plant available water. The optimum biochar percentage addition makes a biochar soil composite with a higher hydraulic conductivity due to a large and continuous porous system [50]. Five percentage of biochar addition showed more plant available water than 2.5% [58]. The review conducted by Edeh et al. [11] observed that the biochar amendment > 30 t/ha and < 30 t/ha was feasible for coarse- and fine-grained soils, respectively.

It is interesting to note from Fig. 5a that there is a tendency of bimodal behaviour for SWCC corresponding to clay content of 6% and biochar content of 5.4%. This might be a possibility due to dual porous structure depicted by simultaneous presence of significant amount of clay and biochar content. Also, as understood from the literature, some biochars [5, 56] may depict dual porous structure itself, whose effect on water retention behaviour of soils needs to be investigated. Further studies are needed to explore potential of different types of biochars, namely from plant-based and animal-based for understanding their effect on water retention behaviour of soils.

3.3 Influence of biochar types on soil with higher sand content

Figure 6 shows the influence of biochar content on SWCCs of soil with higher sand content (i.e., 90%). It can be observed that with an increase in biochar content, there is a slight increase in NWC of soil at the wetter side of SWCC. On the other hand, the change in NWC on the drier side of SWCC is insignificant with an increase in biochar content (except for 10%). The observation is different from that of soils with a relatively higher ratio of fine to coarse content (refer to Fig. 4a, b). It was found in Fig. 4a, b that the influence of biochar is relatively more on the drier side of SWCC than on the wetter side. There was a threshold clay content, beyond which the effect of biochar was significant on the wet and dry side of SWCC. It was found in Fig. 6 that the presence of excessive biochar (i.e., 10%) can cause a reduction in NWC. This implies that for soil with a very high sand content, there is a relatively high requirement of biochar content (at least 10%) for causing a significant change in NWC. Previous studies revealed the effects of
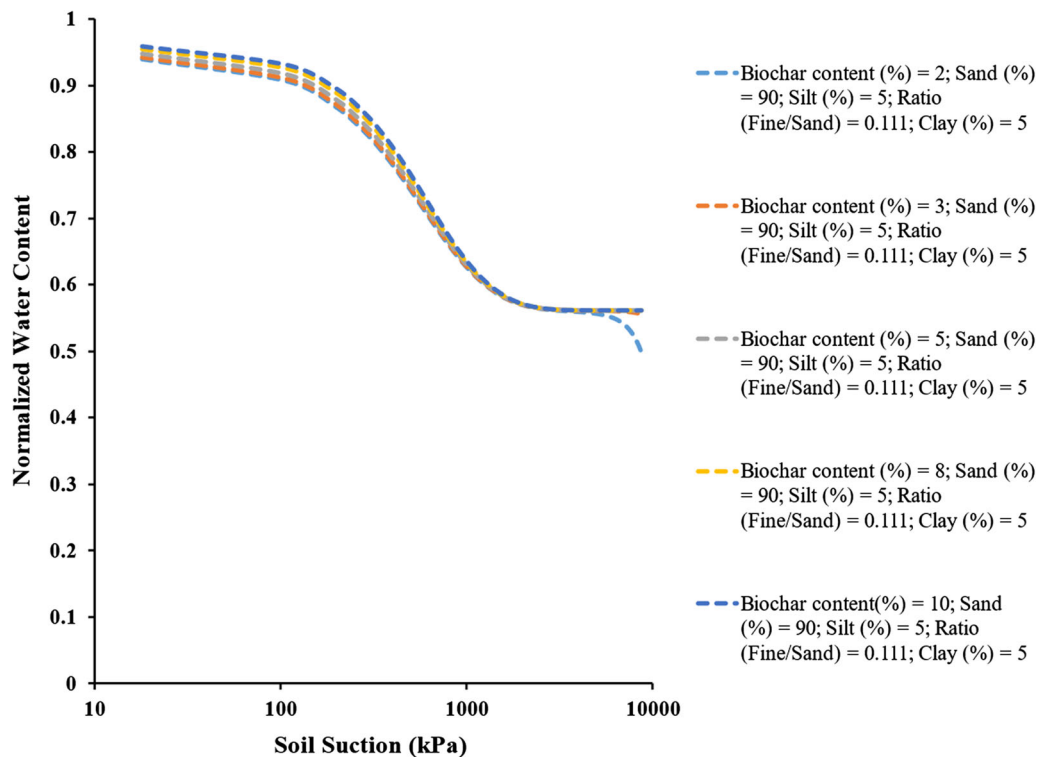
Fig. 6 Variation of NWC and soil suction at different biochar contents for soil with higher sand content

biochar on hydraulic characteristics [64]. Biochar amendment increases the water retention capacity, which is also influenced by biochar feedstock, pyrolysis temperature, pyrolysis duration and soil types [36]. Arthur et al. [4] observed an increase in WRC due to biochar at a high suction range in non-compacted sandy loam soil.

It should be also noted from Figs. 5 and 6 that the influence of void ratio on SWRCs is not explicitly considered. This is because the developed ANN model is based on data from the heterogeneous sources including studies from agriculture, hydrology and geotechnical engineering, where soil densities have contrasting differences. Further, very few studies have reported void ratio or soil density (in terms of degree of compaction) in their studies. Studies from geotechnical engineering perspective [6, 15, 41, 64] reported degree of compaction of 70–95%, while those from agricultural studies reported soil density in terms of 1.3 g/cm^3 [43]. It is well known that initial void ratio affects the SWCC behaviour [72, 73]. Zhai et al. [72] established framework based on pore-size distribution framework for estimating SWCCs. A considerable change in water retention behaviour is observed especially in the lower range of suctions before residual zone. Further studies are needed to quantify the effect of different initial void ratios on SWCCs of biochar amended soils before considering it for model development.

It can be found from Fig. 7 that the ratio of fine to sand content is the most influential parameter affecting NWC (Fig. 7). The ratio of fine to sand content indirectly influences the microstructural arrangement and hence water retention capacity. This is followed by sand content, silt content and soil suction. Interestingly, biochar content seems to be the least important parameter among all. The results seem to suggest that the ratio of fine to sand content is an important parameter while determining the efficiency of biochar. It should be noted that the conclusions are based on a limited set of data, and any influence of soil compaction and feedstock type of biochar is not taken into account.

4 Conclusion

This study aims to analyse the efficiency of biochar on SWCC of soil with varying grain size distributions. A new factor (ratio of fine to sand content) was defined to understand the extent of influence of biochar on SWCC. The ANN-based model was found to predict SWCC reasonably well. Based on predictions, it was found that there is a threshold clay content (6–8%) beyond which any effect of biochar becomes less significant. However, for soils with higher sand content, there is a slight increase in normalized water content on the wetter side of SWCC with the
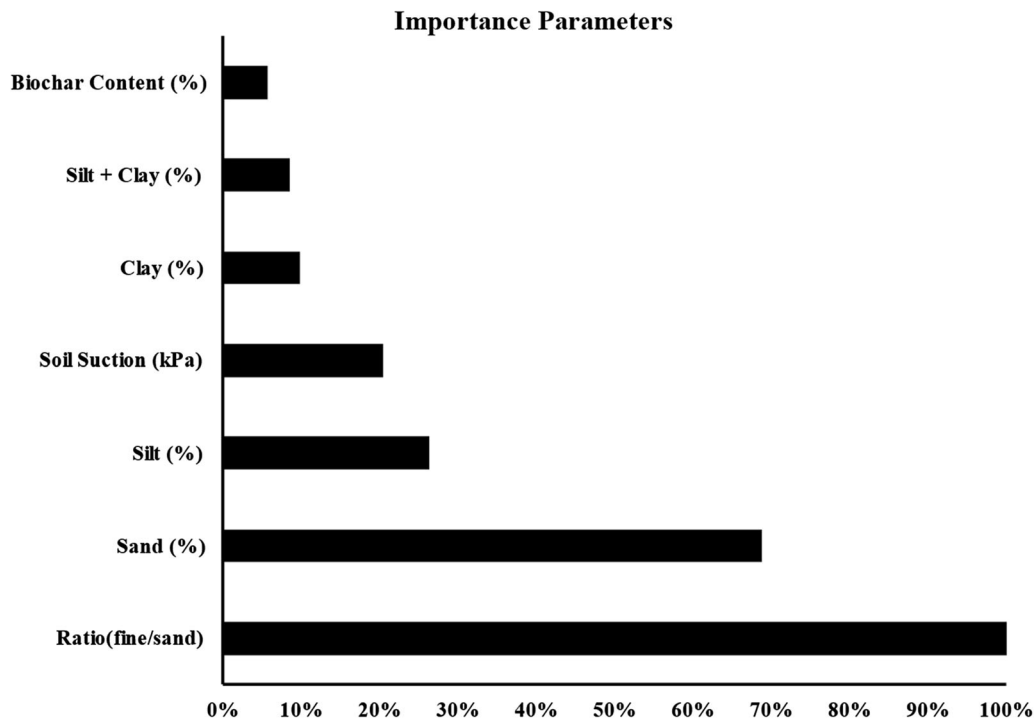
Fig. 7 Relative significance of parameters affecting SWCCs

presence of biochar. A relatively higher amount of biochar (i.e., 10%) is required for causing changes in the drier side of SWCC for sandy soils. Based on sensitivity analyses, the ratio of fine to sand content was also found to be the most important factor causing changes in NWC. This is because the ratio indirectly influences the microstructural arrangement and hence soil water retention capacity.

In contrast, biochar content was found to be comparatively least influential. It should be noted that the above conclusions are based on the given set of measured data that was available in the literature. Further, there is also a lack of reliable data of SWCC at the higher range of soil suction and also for various types of biochar produced from different feedstock types. More systematic studies need to be conducted to establish full-scale SWCC for soils amended with various types of biochars (i.e., animal-based and plant-based). In addition, probabilistic approaches and Bayesian optimization techniques [59, 60, 75] can be adopted for considering uncertainties in measured SWCCs.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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