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ORIGINAL ARTICLE

Water retention models for soils mixed with waste residues: application of the modified van-Genuchten and Brooks-Corey models

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Abstract

Applying additives (e.g., biochar and rapeseed-oil residue) to soils is a common agronomic practice used to improve water-retaining capacity. An investigation of water availability and an applicability evaluation of traditional soil water retention curve (SWRC) are therefore necessary for the soil mixed with waste residues. We aimed to investigate the impact of additives on water retention and further to develop models for their prediction. Loam and sandy loam were mixed with different amounts of rapeseed-oil residue and biochar, respectively. And results show that the biochar and rapeseed-oil residue retain more water, with a minimum and maximum increase in soil moisture by approximately 26.2% and 92.7%, and 10.2% and 19.4%, respectively, relative to pure soil. Furthermore, based on the soil capillary theory, modified van–Genuchten (M-VG) and Brooks–Corey (M-BC) models were constructed and compared, which indicate that both the modified physics-based models (M-SWRC) have higher accuracy than the traditional SWRC models in soil moisture prediction; furthermore, the M-VG model outperforms the M-BC model, due to larger R^2 and smaller *MAPE* and *RMSE*. For the field soils mixed with additives, the soil suction density function has potentials for SWRC model modification based on the soil capillary theory.

Keywords Parameter fitting · Water retention · Biochar · Rapeseed-oil residue · Van–Genuchten/Brooks–Corey model

1 Introduction

Soil additives, such as crop straws and byproducts of plant processing, are generally applied to field cultivated soils for enhancement of soil water retention. For example, biochar is a porous and carbon-rich material produced through the heating of natural organic materials under oxygen-limited or oxygen-free conditions [1]. The feedstock type is one of the dominant factors affecting the characteristics of biochar [2]. Most of the biochar materials have been extensively preferred to be made from crop straw (e.g., wheat, maize, switchgrass, rice husk, etc.), woodchips and sawdust, beechwood, and wastewater sludge [1, 3–5], which are harmless and may not bring threats to the environment. *Eichhornia crassipes*, also well known as water hyacinth, however, is one type of the worst weed. An exploration of whether it can be processed into biochar is of importance to environmental protection. For this purpose, the impact of such biochar on water retention was investigated in the present study. It is expected to contribute to a reduction in environmental pollution. In recent years, biochar has been widely selected as a sustainable soil amendment for improving soil fertility [6, 7], soil microbial activity [8, 9], and water retention [10], thereby increasing crop yield [5]. However, scholars paid more attention to impacts of biochar on the in situ soils on farmland (i.e., non-compacted soil) and investigated the water-holding capacity through soil sampling. The water retention behavior of non-compacted soil may be different from compacted soil since water retention depends on soil pore space, which is influenced by compaction. In this regard, further study is still necessary. In addition, the rapeseed-oil residue, another type of easy-produced and harmless soil fertilizer, attracts little attention, although it has been

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reported [11]. And the impact of rapeseed-oil residue on water-retaining capacity of the compacted soil remains unclear. Reasonable management of the soil water content status and a clear understanding of compacted soil hydraulic properties are crucial for agriculture and engineering issues. Thus, for the selected compacted soils in the current study, the data of soil moisture and suction were monitored simultaneously. It lays a foundation for construction of soil water retention curve (SWRC) and also for water availability investigation.

SWRC represents the soil's ability to store or release water when it is subjected to soil suction, which is the basis of the derivation of soil hydrodynamic parameters and numerical simulation of soil water distribution [12, 13], as well as the foundation of soil physics and soil hydrology. Many scholars have widely studied SWRC fitting of various soils [14, 15] and influential factors of SWRC [16–18], achieving some mature developments. Also, SWRC is widely adopted to evaluate soil water availability as well as to analyze soil hydraulic characteristics [19]. For the research on transport and modeling of soil water and solute, SWRC also plays a fundamental role in determining the model's input parameters [20, 21]. Most researches were mainly focused on pure soils, potentially limiting the applicability of the relevant achievements to the soil mixed with additives, which is just common in cultivated fields. As a result, the research on hydraulic characteristics of such soil composites is imperative with practical significances.

Furthermore, the van–Genuchten (VG) model and the Brooks–Corey (BC) model are widely adopted for SWRC modeling [22]; however, they are established based on uniform soil, which is different from the soils mixed with additives. Under such circumstances, soil pore size and distribution change due to the application of soil additive, which is a major physical mechanism resulting in the changes in water retention [23–26]. The traditional SWRC model therefore needs considerations of the additive effects on soil suction density function based on soil capillary theory for re-construction. As has been reported by Xing and Ma [27] that the established modified VG model was effective for soils mixed with wheat residues, and based on the prior research, the BC model will also be modified, expecting that the soil capillary theory has potentials for SWRC model modification for field soils mixed with additives. As a result, the research on model modification for such soil composites is of theoretical significance.

From the above, an assessment of water retention and a modification of water retention model in relation to the compacted soil mixed with additives will be of practical and theoretical significances as well as contribute to environmental protection. This study therefore focused on the practical and theoretical influences of biochar and rapeseed-oil residue on hydraulic characteristics of water retention, with main objectives of (1) investigating SWRC property for the compacted loam and sandy loam textured soil mixed with rapeseed-oil residue and biochar at different application amounts; and (2) extending the soil capillary theory to different SWRC models for comparisons and further determining the appropriate model.

2 Experimental materials and design

2.1 Soil and additives

Loam and sandy loam utilized in this study were selected from Yangling in Shaanxi Province (about 34°17′ N, 108°04′ E) and Shantou in Guangdong Province (about 23°24′ N, 116°36′ E), respectively. Both soils are representative due to their wide distribution in the local farmland. The fractions of sand, silt, and clay for the loam soil are 38.4%, 44.3%, and 17.3%, respectively, whereas for the sandy loam soil they are 58%, 37%, and 5%, respectively. Besides, the liquid limit and plastic limit for the loam soil are 33% and 18%, respectively, whereas for the sandy loam soil they are 42% and 26%, respectively. The maximum dry density for the loam and sandy loam is approximately 1.8 and 1.6 g cm^{-3}, respectively.

Biochar and rapeseed-oil residue served as additives to improve the water availability of compacted soils. Specifically, the biochar was obtained via processing the water hyacinth plant, and the detailed processing method was presented in the report by Bordoloi et al. [26]. The rapeseed-oil residue was obtained after extracting oil of *Perilla frutescens* seeds.

2.2 SWRC measurement

According to the regular additive content in the local cropland, the percentage of biochar was set to 5%, 10%, and 15% (5B, 10B, and 15B); and the percentage of rapeseed-oil residue was set to 1%, 1.5%, and 2% (1R, 1.5R, and 2R). Pure soil (PS) samples without additives were used as the control treatment. Each type of soil sample has three replicates.

The soil mixed with different percentages of biochar was compacted using a static compaction method in Poly Vinyl Chloride cylinders of 300 mm in diameter and 250 mm in height. Compacted samples were then transferred to a greenhouse, exposed to a controlled environment and irrigation (wetting) during the monitoring period. For irrigation, the sprinkler was attached on top of each soil column. Irrigation of around 1000 mL at a 7-day interval was applied. Soil matric suction (at 30 mm depth) was measured using an MPS-6 sensor [28], and the adopted maximum measurement value is 1000 kPa. Soil moisture (at 30-mm depth, as it is commonly found within the root zone of agricultural farmland crops) was measured using an EC-5 sensor [28]. The monitoring period of 63 days consists of 9 drying-irrigation cycles. During this monitoring period, suction and moisture content were simultaneously monitored.

Soils mixed with different percentages of rapeseed-oil residue were compacted into cutting rings of 50 mm in diameter and 510 mm in height. All samples were soaked in distilled water for 48 h. After saturation, the centrifugal method was adopted to measure the SWRCs, and the adopted maximum measurement value of soil matric suction is 700 kPa. All soil samples were dehydrated at speeds corresponding to a specific suction, and after the equilibrium time for a certain suction was reached, the soil samples were removed from the centrifuge and weighed using an electronic balance. All soil samples were oven-dried at the end of the centrifugation at 105 °C to constant weight for soil moisture calculation [29]. The data of suction and moisture content were finally simultaneously obtained.

2.3 SWRC models

Based on VG and BC models proposed by van Genuchten [30] and Brooks and Corey [31], SWRC was described by Eqs. 1 and 2, respectively, which are both semi-empirical in nature [32].

$$\theta = \frac{\theta_s - \theta_r}{\left[1 + (\alpha h)^n\right]^m} + \theta_r \tag{1}$$

$$\theta = \frac{\theta_s - \theta_r}{(\alpha h)^n} + \theta_r \tag{2}$$

where θ represents the volumetric water content (cm^3 cm^{-3}); θ_s and θ_r represent the saturated and residual volumetric water content (cm^3 cm^{-3}), respectively; α represents the inverse of the air-entry value; h represents soil suction (cm); m and n represent curve-shape factors.

Based on the reports by Xing and Ma [27] and Xing et al. [33], the traditional VG model was modified by combining with the soil capillary theory (Eq. 3). The BC model can be therefore modified as Eq. 4 by using the same approach, with the combination of a simplification method proposed by Mualem [34]. The genetic algorithm (GA) has been successfully applied to determine SWRC [19, 35], which was therefore adopted to calibrate parameters in the Eqs. 3 and 4 based on the measured SWRC data and further to construct the modified van-Genuchten (M-VG) and modified Brooks-Corey (M-BC) models.

$$\theta = \theta_{sp} \cdot \left[1 + (\alpha h)^{n_p}\right]^{-m_p} + \theta_{sq} \cdot \left[1 + (\alpha h)^{n_q}\right]^{-m_q} + \theta_r \tag{3}$$

$$\theta = \theta_{sp} \cdot (\alpha h)^{-n_p} + \theta_{sq} \cdot (\alpha h)^{-n_q} + \theta_r \tag{4}$$

where θ_{sp} and θ_{sq} represent saturated water content for the pure soil and increased saturated water content resulted from adding biochar, respectively. They could be obtained through the cutting-ring method [18].

2.4 Model performance evaluation

Mean absolute percentage error (*MAPE*), root mean square error (*RMSE*), and determination coefficient (R^2) were used as statistical indicators (Eqs. 5–7) to evaluate the SWRC models. And the model will have high simulation efficiency when the values of *MAPE* and *RMSE* are closer to 0 and the value of R^2 is closer to 1.

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{M_i - S_i}{M_i}\right| \times 100\% \tag{5}$$

$$RMSE = \sqrt{\frac{1}{n} \cdot \sum_{i=1}^{n}\left(S_i - M_i\right)^2} \tag{6}$$

$$R^2 = \left[\sum_{i=1}^{n}\left(S_i - \overline{S_i}\right) \cdot \left(M_i - \overline{M_i}\right)\right]^2 \Big/ \sum_{i=1}^{n}\left(S_i - \overline{S_i}\right)^2 \cdot \sum_{i=1}^{n}\left(M_i - \overline{M_i}\right)^2 \tag{7}$$

where n is the sample size; M_i and $\overline{M_i}$ represent the observed soil water content and mean soil water content, respectively; S_i and $\overline{S_i}$ represent the predicted soil water content and mean soil water content using models, respectively.

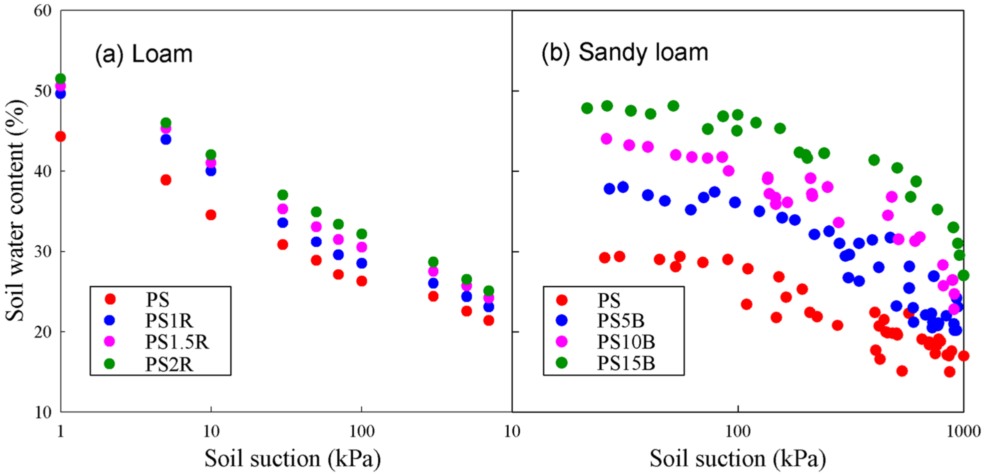
3 Results

3.1 Impacts of additives on water retention of the compacted soil

The SWRC property that represents the change of compacted soil moisture with suction for the data series is displayed in Fig. 1. For each treatment, the soil water content decreases at different rates with the increasing soil suction. In general, soil drainage mainly occurs in the macropores under low suctions, in which case, the soil water content can change considerably under a slight variation of soil suction condition. As soil suction continues increasing, soil water mainly reserves in the relatively small pores that have large holding force on water.

For the selected loam soil (Fig. 1a), the saturated soil moisture increases with the application amount of rapeseed-oil residue, specifically by approximately 45%, 50%, 51%, and 52% for pure soil and the soil mixed with rapeseed-oil residue at a percentage of 1%, 1.5%, and 2%, respectively; moreover, the average soil moisture is (29.92 ± 7.36) %, (32.99 ± 8.82) %, (34.46 ± 8.67) %, and (35.71 ± 8.58) %, respectively. For the selected sandy loam soil (Fig. 1b), the saturated soil moisture increases with the application amount of biochar, specifically by approximately 30%, 38%, 42%, and 48% for pure soil and the soil mixed with biochar at a percentage of 5%, 10%, and 15%, respectively; moreover, the average soil moisture is

Fig. 1 Impacts of rapeseed-oil residue and biochar on water retention for loam and sandy loam soils



(21.51 ± 4.35) %, (27.14 ± 5.71) %, (34.04 ± 6.02) %, and (41.46 ± 6.33) %, respectively.

Furthermore, the increase in water retention capacity is proportional to the additive percentage added to the soil, with a rate of increment at about 26.2%, 58.2%, and 92.7% for the PS5B, PS10B, and PS15B treatment, respectively, and about 10.2%, 15.2%, and 19.4% for the PS1R, PS1.5R, and PS2R treatment, respectively, relative to the pure soil. This finding verifies the effectiveness of the rapeseed-oil residue and biochar on the water-holding capacity of the compacted soil.

3.2 Parameter estimation of M-SWRC models

The established M-SWRC models (i.e., M-VG and M-BC) divide the traditional SWRC model into two parts, which are the pure soil term and the additive term. These two terms depend on pure soil and the applied additive, respectively. In the present study, the soil structure changes after the application of biochar. It was considered during the establishment of the M-VG and M-BC models. Such consideration of the physical process of additives affecting soil pores strengthens the physical foundation.

For the loam mixed with rapeseed-oil residue and the sandy loam mixed with biochar, the fitted parameters in the M-VG and M-BC models (Tables 1 and 2) show a decreasing and an increasing tendency of α and θ_r, respectively (except for the α value for PS15B of the M-BC model), with the increasing application amount of additives. It is in accordance with the practical circumstance. As shown in Figs. 2 and 3, the water-holding capacity gradually increases in an order of PS1R < PS1.5R < PS2R and PS5B < PS10B < PS15B, respectively. It also results in an increase in the value of air-entry suction, which will cause decreases in α; meanwhile, the increase in water retention because of the increasing addition also raises soil hygroscopic water, which will cause increases in θ_r. The M-VG and M-BC models were run after parameter estimation. Specifically, from Fig. 2, only slight differences in general are observed between the M-VG and M-BC models. However, the measured soil moisture data distribute tightly along with the M-VG model; in addition, the M-VG model is more accurate under very low suction conditions. From Fig. 3, significant differences occur between the M-VG and M-BC models, and the measured soil moisture data distribute compactly along the M-VG curve. In all, compared with the M-BC model, the M-VG model can better predict the soil moisture at low and high suctions.

3.3 Error analysis of SWRC models

The traditional SWRC models and the M-SWRC models were adopted to fit the data for the soils mixed with biochar and rapeseed-oil residue. For the two soil types, compared with the BC model, the VG model is more suitable for SWRC fitting, due to relative smaller *MAPE* (maximum absolute value 6.55%) and *RMSE* (maximum 2.73%) and larger R^2 (Table 3). It indicates a good application of the VG model to SWRC evaluation, which matches the fact that this empirical model is used widely because of its broad applicability and high accuracy [36]. Apart from the BC model, the VG model

Table 1 Parameter fitting of the M-VG model

Treatments	α/ ($\times 10^{-2}$)	n_p	m_p	n_q	m_q	θ_r/ (%)
PS1R	64.52	1.77	0.07	1.73	0.64	0.10
PS1.5R	45.94	3.43	0.03	1.31	0.61	0.13
PS2R	32.45	1.17	0.10	4.17	0.25	0.15
PS5B	0.39	1.32	0.22	3.64	0.52	0.02
PS10B	0.20	1.01	0.45	7.01	0.14	0.43
PS15B	0.10	1.04	0.89	5.64	0.53	0.76

α represents the inverse of the air-entry value; θ_r represents the residual water content; n_p and m_p represent curve-shape factors for pure soil term; and n_q and m_q represent curve-shape factors for the additive term

Table 2 Parameter fitting of the M-BC model

Treatments	α/ ($\times10^{-2}$)	n_p	n_q	θ_r/ (%)
PS1R	83.62	0.12	0.41	1.64
PS1.5R	80.66	0.14	0.69	2.04
PS2R	77.03	0.13	0.12	2.70
PS5B	4.00	0.21	0.07	2.08
PS10B	2.07	0.19	0.19	2.35
PS15B	11.99	0.09	0.09	4.55

α represents the inverse of the air-entry value; θ_r represents the residual water content; n_p and n_q represent curve-shape factors for the pure soil term and additive term, respectively

has also been established for homogeneous soils, and SWRC is often affected by soil texture and structure [37]. Therefore, these two models have weaker reliability than the M-SWRC models because the soil becomes inhomogeneous after application of additives in the present study.

The M-VG and M-BC models, however, were established considering the impacts of biochar and rapeseed-oil residue on soil pores. The error analysis (Table 3) demonstrates that for the sandy loam mixed with biochar, the R^2 of M-SWRC models are always over 90.00%, larger than that of traditional SWRC models. In addition, for the M-VG and M-BC models, the maximum *MAPE* values are 3.56% and 9.00%, respectively, and the maximum *RMSE* values are 1.47% and 3.94%, respectively. They are all obviously smaller than those of the VG and BC models. For the loam mixed with rapeseed-oil residue, smaller *MAPE* and *RMSE* values for the M-VG and M-BC models are also observed, compared with the VG and BC models. Also, the R^2 values for the SWRC models are at roughly equal levels. From the above, the M-SWRC models are more feasible and effective for determining the SWRCs of such soil composites. To be more specific, the M-VG model with larger R^2 and smaller *MAPE* and *RMSE* outperforms the M-BC model, which can also be found in Figs. 2 and 3.

4 Discussion

4.1 Improvement of water availability for compacted soil

Such compacted soil composites may be of importance in engineering, such as being used as alternative slope/landfill final cover soil. Therefore, the current retention investigation to water of the compacted soil mixed with water-holding materials has practical implications. Figure 1 demonstrates that both biochar and rapeseed-oil residue can obviously improve the water retention capacity of the compacted soil, which is primarily attributed to the changes in the soil pore size distribution and capillary action [29, 38]; besides, the high porosity is another reason for their ability to store and retain water [26, 39, 40]. Furthermore, the presence of the hydrophilic oxygen-containing functional groups gives evidence to the increased retention [33].

For the compacted soil, the degree of compaction (i.e., soil density) has profound influences on water retention behavior; also, the soil aggregates formed during compaction affect soil moisture [41]. In further studies, the combined actions of density and additives and the impacts of additives on those factors affecting water retention (e.g., soil aggregate) should be considered.

4.2 Applicability of SWRC and M-SWRC models for soils mixed with waste residues

Both VG and BC models are popular, but also have some limitations caused by the particular mathematical assumption of the equation describing the SWRC. Specifically, BC model does not include an inflection point. Rather it identifies clearly a distinct air-entry value that separates the SWRC into two distinct zones (i.e., saturated and unsaturated). Therefore, the BC equation is especially apt for soils exhibiting a well-defined air-entry value saturated zone and "J"-shaped retention curve [42]. On the contrary, the VG model is

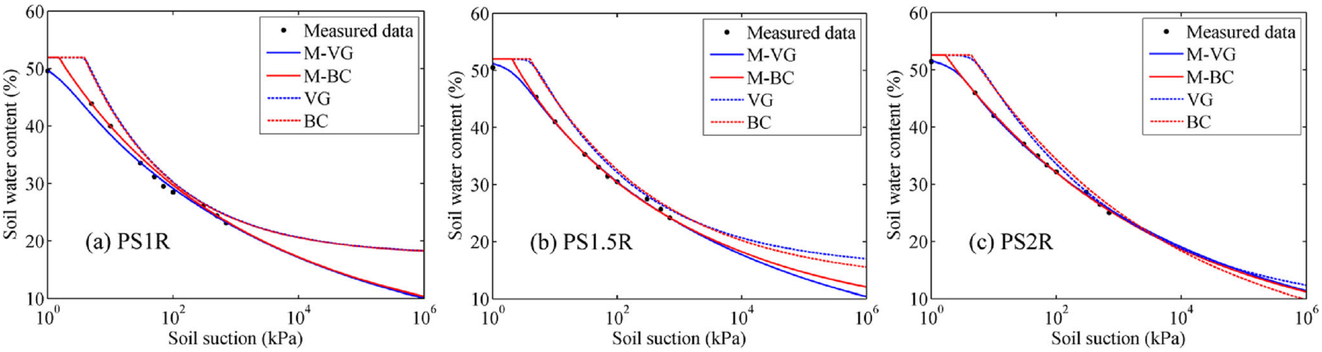


Fig. 2 Comparison of measured soil moisture and predicted soil moisture obtained from M-SWRC and SWRC models for the loam mixed with rapeseed-oil residue

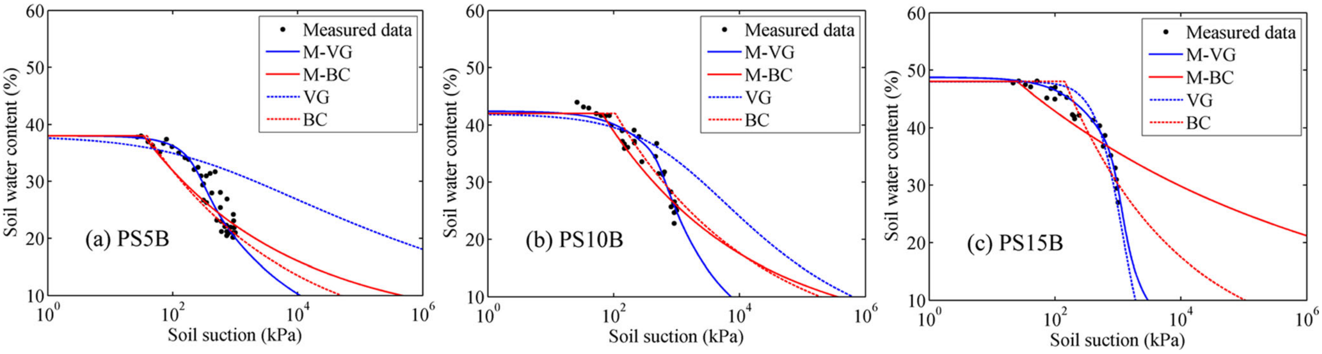


Fig. 3 Comparison of measured soil moisture and predicted soil moisture obtained from M-SWRC and SWRC models for the sandy loam mixed with biochar

characterized by the absence of distinct air-entry value and there is not a distinct separation of the two regions existing in the BC model [43]. From the above, the VG model performs better than BC model, as listed in Table 3.

The biochar and rapeseed-oil residue in this study changed the soil structure and pores, and the soils became inhomogeneous under such circumstances, which may therefore result in weak reliability of the traditional VG and BC models. As Xing and Ma [27] reported that the modified VG model based on the soil capillary theory was capable of moisture prediction for the field soils mixed with wheat straws, in order to further verify whether this theory is applicable to other SWRC models and additives, we selected biochar and rapeseed-oil residue as soil amendments for different soils and tried to apply this theory to the BC model. Table 3 and Figs. 2 and 3 indicated that the introduced M-SWRC models can be utilized for such soil composites and different soils, performing better than the traditional SWRC models, which justifies the combination of the SWRC model with soil capillary theory. Such consideration of the physical process of additives affecting soil pores will strengthen the physical foundation and benefit further research on model mechanisms.

For actual cropland, applying additives to soils is a common agronomic practice for water retention improvement; therefore, the established M-SWRC models are theoretically more suitable than the traditional SWRC models. Therefore, in the future studies on hydraulic characteristics for such soils, the proposed modified SWRC models are recommended. Furthermore, although the adopted traditional GA was capable of calibrating the parameters in the M-VG and M-BC models, some improved programming technology still needs to be developed to improve the precision of parameter calibration. For example, the traditional GA has potentials to be improved with combinations of multi-objective optimization and elitist strategy, which can solve the problems caused by the standard GA. Besides, the Bayesian methods can be used to accurately estimate the unknown parameters and associated uncertainties [13, 20, 44–46], which also have potentials to be employed for inversing hydraulic parameters in the M-SWRC models.

4.3 Application of the biochar and rapeseed-oil residue

Both biochar and rapeseed-oil residue are soil fertilizers, and they can be applied to soils during plowing, which means an easy operation in cropland. In addition, the selected rapeseed-oil residue is a byproduct of vegetable oil

Table 3 Error analysis of SWRC models for the soils mixed with additives

Treatments	*MAPE*/(%)				*RMSE*/(%)				R^2/(%)			
	VG	BC	M-VG	M-BC	VG	BC	M-VG	M-BC	VG	BC	M-VG	M-BC
PS1R	6.55	9.72	0.29	2.88	2.65	6.74	0.85	1.92	98.92	94.02	99.16	98.08
PS1.5R	6.17	9.61	0.33	1.18	2.58	5.38	0.41	2.62	98.59	96.82	99.82	96.73
PS2R	5.42	9.29	0.02	0.81	2.73	5.02	0.27	1.45	98.72	96.48	99.89	98.68
PS5B	5.15	6.10	3.56	5.61	1.77	2.50	1.33	2.30	92.33	90.05	95.98	90.15
PS10B	3.42	5.10	3.10	4.99	1.71	2.68	1.47	2.30	92.37	90.74	93.01	90.82
PS15B	4.61	9.25	2.49	9.00	2.17	4.23	1.16	3.94	95.95	90.35	97.73	80.04

VG and BC represent the traditional van–Genuchten and Brooks–Corey models, respectively. M-VG and M-BC represent the modified VG and BC models, respectively, in relation to the soils mixed with additives extraction of the *Perilla frutescens* plant, one type of common herbaceous plant widely distributed in a farmland where it has fertile soil and warm environment. In view of its high oil content, amino acid, and mineral elements of seeds, it has high medicinal and edible values and can be used as an industrial raw material. Furthermore, the processing technic of rapeseed-oil residue is easy and inexpensive without special technique and equipment. These can therefore help reduce the farmland input-to-output ratio, which is a top priority for farmers. The currently selected biochar, a charred byproduct of plant biomass generated during pyrolysis or gasification, was obtained from water hyacinth plant. It is widely distributed in shallow water, and its rapid propagation easily causes insufficient fresh air and food of animals as well as poor photosynthesis of other plants. The IUCN organization has therefore listed it as one of the world's most invasive species, which can destroy ecological balance of the water body, cause reduction in biodiversity, block waterways, and incur millions of dollars in controlling [47]. The conversion of such waste biomass to biochar will reduce environmental pollution. Therefore, recycling waste material and making waste profitable are crucial to sustainable development and deserve more attention.

5 Conclusions

Application of biochar and rapeseed-oil residue is helpful to improve the water retention capability of the compacted soil, which shows an increasing tendency with the increases in application amount. The average soil moisture increases by 26.2%, 58.2%, and 92.7% for the sandy loam mixed with biochar at a percentage of 5%, 10%, and 15%, respectively, and 10.2%, 15.2%, and 19.4% for the loam mixed with rapeseed-oil residue at a percentage of 1%, 1.5%, and 2%, respectively, relative to pure soil. Furthermore, the utilization of such additions is expected to reduce soil and environmental pollution. Moreover, for the field soils mixed with additives, the soil suction density function has potentials for SWRC model modification based on the soil capillary theory. Specifically, the established M-VG and M-BC models display higher simulation accuracy than VG and BC models in SWRC determination for such soil composites, due to larger R^2 and smaller *MAPE* and *RMSE*. Among them, the M-VG model performs better.

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