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Influence of in-house produced biochars on cracks and retained water during drying-wetting cycles: comparison between conventional plant, animal, and nano-biochars

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Abstract

Purpose Biochars produced from different feedstocks (such as wood, pig manure) possess varying physical and chemical properties, which have influence on crack and evaporation rate of biochar-amended soil (BAS). Furthermore, influence of compaction state and drying-wetting cycles on evaporation rate and cracking of BAS has not been investigated comprehensively. The objective of this study was to investigate the effects of biochar types, compaction state of BAS, and drying-wetting cycles on crack propagation and retained water (or evaporation rate).

Material and methods An animal and plant feedstock-based biochars were produced in-house from pig manure (PM) and wood (W), respectively. In addition, nano structured chalk and wheat biochar (CWB) were also produced. Soil amended with individual biochars was compacted in petri-glass discs at two densities. Disc specimens were subjected to multiple drying-wetting cycles, and evaporation rate of specimens and crack area were monitored throughout the experimental period (70 days). Images were captured after every 24 h and processed using image processing technique to obtain the crack intensity factor (CIF).

Results and discussion The results show that plant-based W BAS showed the high water retention, i.e., low evaporation rate and low CIF. Furthermore, the crack potential of CW BAS was seen to be higher. In dense compacted soil, maximum CIF% can be reduced from 3.9 to 0.4% for W BAS, from 3.9 to 1.7% for PM BAS, and from 3.9 to 1.6% for CW BAS.

Conclusion WB was able to resist cracking more efficiently than other types of biochar. Evaporation was found to be minimal for plant-based W BAS at 10% biochar percentage. Higher biochar content in soil was seen to increase the water retention of BAS significantly. Dense state of BAS at high biochar content (i.e., 10%) was effective in reducing evaporation rate and crack progression.

Keywords Biochar amended soil · Compacted soil · Evaporation rate · Cracks · Water retention

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Nomenclature

ASTM	American Society of Testing and Materials
BAS	Biochar amended soil
CIF	Crack intensity factor
CW	Chalk and wheat nano-biochar
DoC	Degree of compaction
FE-SEM	Field emission scanning electron microscope
FTIR	Fourier transform infrared spectroscopy
LL	Liquid limit
MDD	Maximum dry density
MLCS	Multilayered cover system
OMC	Optimum moisture content
PL	Plastic limit
PM	Pig manure biochar
RGB	Red green blue

USCS	Unified Soil Classification System
WB	Wood biochar

1 Introduction

Biochar is a form of biomass, which is produced by burning the plant or animal biomass in the presence of limited or no oxygen (Brown 2012; Lehmann and Joseph 2015). Addition of biochar in soils can effectively improve many geo-environmental and agricultural soil properties such as water holding capacity (Basso et al. 2013), nutrient availability (Chan and Xu 2009), erosion potential (Jien and Wang 2013; Kumar et al. 2019), gas permeability (Wong et al. 2016), mechanical strength (Zong et al. 2014; Sadasivam and Reddy 2015; Zhou and Qi 2018; Zhou et al. 2019), and pollutant removal (Chen et al. 2018; Zhou and Qi 2018; Chen et al. 2019). In geo-environment applications such as landfill covers, biochar was added in compacted soil to reduce the emission of greenhouse gases (carbon dioxide and methane) (Manfredi et al. 2009), increase the mechanical strength of biochar amended soil (BAS) (Zong et al. 2014), and reduce the erosion potential at early plant establishment (Kumar et al. 2019). Furthermore, in agricultural applications, presence of biochar enhances the nutrients availability in soil (Laird et al. 2010) increases the water retention capacity of soil (Bruun et al. 2014) and restricts the pathway to harmful pesticide into ground water (Peng et al. 2016).

Around 50.8 million m^3 of lignocellulosic wood log and 12-million-ton manure are generated in Brazil annually (Schneider et al. 2012a, b). On the other hand, biochar obtained from wood have high potential for improving C storage in tropical soil due to higher aromatic character, high C concentration, and FTIR spectra features as compared to nutrient-rich biochars (Domingues et al. 2017). High ash content due to labile organic and inorganic compounds in pig manure was reported to improve the soil acidity and increases the soil cation exchange capacity (CEC) (Singh et al. 2010; Wan et al. 2014). Nano-biochar was reported to have ultrafine particles and high specific surface area (SSA). Therefore, CW biochar has been utilized as a potential material for the removal of pollutant from soil (Chen et al. 2018; Zhou et al. 2019; Chen et al. 2019). As per the authors' current knowledge, no literature is available which discusses the behavior of nano structured BAS with respect to geo-environmental and agricultural perspective. This study highlights the effect of nano-biochar particle on soil cracks and evaporation rate which can help to select suitable biochar for landfill cover application.

Soils used in landfill covers are highly compacted for preventing water infiltration into waste and transportation of greenhouse gas into atmosphere generated from degradation of waste (Mohareb et al. 2011). Desiccation cracks in soil is considered as threat for various geo-environmental and agricultural applications. These applications include multi layered cover system (Li et al. 2016), embankment slopes (Chowdhury and Zhang 1991), dam failure (Talbot and Deal 1993), green infrastructures (Bordoloi et al. 2018a; Garg et al. 2019a, b; Gopal et al. 2019), and high water-holding capacity for plant (Bruun et al. 2014). During the drying-wetting cycles of atmosphere, development of desiccation cracks at surface layer of landfill cover permits water to infiltrate into solid waste which may lead to the landfill cover failure. On the other hand, agricultural soils are relatively loose for root penetration and retain more water (Bruun et al. 2014). In this study, shrinkage and fracture cracking was investigated which are formed and propagated naturally subject to cyclic drying-wetting paths (Alonso et al. 2005). There are very few studies which elucidate the effect of drying-wetting cycle and compaction state on cracks and evaporation rates for BAS, especially with contrasting biochar types (Albrecht and Benson 2001). Severe cracking of unprotected clay barriers due to desiccation cracks was reported in many field studies (Montgomery and Parsons 1990; Benson et al. 1993; Khire et al. 1997). However, in terms of geo-environmental perspective, surface layer of compacted landfill covers was not investigated thoroughly, considering the effect of biochar type and compaction state of BAS (Zhou et al. 2014; Zhou et al. 2017a, b). Furthermore, effects of biochar percentage, degree of compaction (DoC), and drying-wetting cycles on evaporation rate and cracks are rarely investigated.

In literature, researchers have often adopted biochar (Wong et al. 2016; Ni et al. 2018), fibers (Bordoloi et al. 2018a), cementation (DeJong et al. 2010), and vegetation (Li et al. 2016; Gadi et al. 2018) for suppression of soil cracking. Bordoloi et al. (2018a, b) reported that in the presence of biomaterial such as water hyacinth biochar, water retention increases and cracks in unsaturated biochar amended soils decreases significantly and cracks in samples were quantified as CIF. Furthermore, study was limited to single-type biochar (plant-based water hyacinth biochar (WHB)) and the thickness of samples is enormous (about 25 cm) compared to total surface area of samples. However, influence of BAS density, various biochar types, and number of drying-wetting cycles on cracks was rarely investigated. The water retention during drought is important for plant growth and survival. Many researchers from agriculture and soil science have extensively investigated physical and chemical properties of biochars, which are produced from different feedstocks (such as plant-based (wheat, maize and corn) and animal-based (poultry litter, PM etc)) and also varying pyrolysis conditions (temperature, rate of heating, nitrogen flow, water content) (Gaskin et al. 2008; Sohi et al. 2010; Laird et al. 2010; Jayawardhana et al. 2016; Gunarathne et al. 2018). As per their studies, biochars produced from different feedstock possesses distinct physical and chemical properties, which may further influence soil properties. Plant-based and animal-based biochar have intrinsic distinctions which lead to various inherent performance on soil or water treatment (Sun et al. 2018; Xu et al. 2014). Because plant-based biochar is derived from plant biomass wastes consisting cellulose, hemicellulose, and lignin, however, animal-based biochar originates from the feces after animal's digestion containing nutrient and other inorganic matter. Comprehensive investigation should be conducted to compare the performance of biochar from various resources (i.e., plant-based and animal-based biochar) and make optimized application strategies for waste management. However, there is rarely any study conducted to evaluate effects of different biochar types on cracking in compacted soil as well as evaporation rate. Such studies are important for preliminary design of landfill cover or slopes, which necessitates a compacted soil subjected to drying-wetting cycles. It is essential to understand what types of biochar could be feasible for its use as cover material in landfill cover or slopes. This will be useful for engineers to narrow down the selection of biochars for use as cover material in landfill cover.

The major objective of this study was to study the effects of different biochar types on retained water (after evaporation) and cracking. Furthermore, the influence of varying biochar percentage, compaction state, and number of drying-wetting cycles on cracking was investigated. To obtain the aforementioned objective wood biochar (WB) and pig manure (PMB) were produced and biochar-amended samples were compacted in petri glass discs. Furthermore, results are compared with newly produced chalk and wheat (CW) nano-biochar. Disc specimens are subjected to drying-wetting cycle till 4th cycle. During the cycles, evaporation rate of specimens and formation of cracks were monitored thought out the experimental period (70 days). Using high-resolution camera, images were captured after every 24 h and every image was analyzed using image processing technique to obtain the CIF. This study will help to improve fundamental understanding of compacted soil-biochar-water-atmospheric interaction.

2 Materials and methodology

2.1 Soil characteristics

In this study, local soil was collected from the Shantou University, China. Soil samples were collected at the 1 m depth from the ground surface. Based on United Soil Classification System (USCS; ASTM D2487–17 2017), soil was classified as *Clayey Sand* (*SC*). The other soil properties were determined as per the American Society of Testing and Materials (ASTM) recommendations. The soil properties such as liquid limit (LL) and plastic limit (PL) were found to be 28.85% and 21.56%, respectively. The maximum dry density (MDD) and optimum moisture content (OMC) of soil are 1.84 g/cc and 13.6 g/cc, respectively. Table 1 shows the basic geotechnical properties of bare soil and BAS.

2.2 Production of biochar and biochar characterization

Plant-based (W) and animal-based (PM) feedstock were collected from local site. Feed stocks were pyrolyzed at 400 °C for 3 h (slow pyrolysis) in the absence of oxygen. Both pyrolyzed WB and PMB were crushed and sieved through 2-mm sieve. Contrarily, dried waste chalk and wheat feedstock was collected and pyrolyzed at a temperature of 400 °C for 8 h (fast pyrolysis). The pyrolysis was executed under a limited supply of oxygen using a portable electromagnetic carbonizer. Ultra-fine powder was obtained using universal high-speed smashing machine (Model-FX-180 power mill grinder; spindle speed-4200r/m). Smashed biochar was sieved using 75-µm sieve size. Finally, the nano-biochar was obtained using a variable frequency planet type grinding mill. Figure 1 shows the systematical steps on the production of WB, PMB, and CWB used in this study. Table 2 represents the particle size distribution of WB, PMB, CWB, and bare soil. It is evident that WB has high percentage of fine particles (42%) than PM biochar (20%). However, the percentage of coarse particle for both biochar are very low ($\leq 3\%$). In

Table 1 Basic characteristics of soil

Samples	Biochar composition	Plastic limit (%)	Liquid limit (%)	Specific gravity	Maximum dry density, MDD (g/cc)	Optimum moisture content, OMC (%)
Bare soil	0%	21.56	28.85	2.61	1.84	13.6
WB	5%	25.99	33.18	2.47	1.72	16.8
	10%	30.89	35.63	2.26	1.63	17.6
	100%	NA	NA	1.17	NA	NA
PMB	5%	26.34	30.38	2.44	1.78	15.2
	10%	33.23	36.33	2.35	1.73	16.0
	100%	NA	NA	1.15	NA	NA

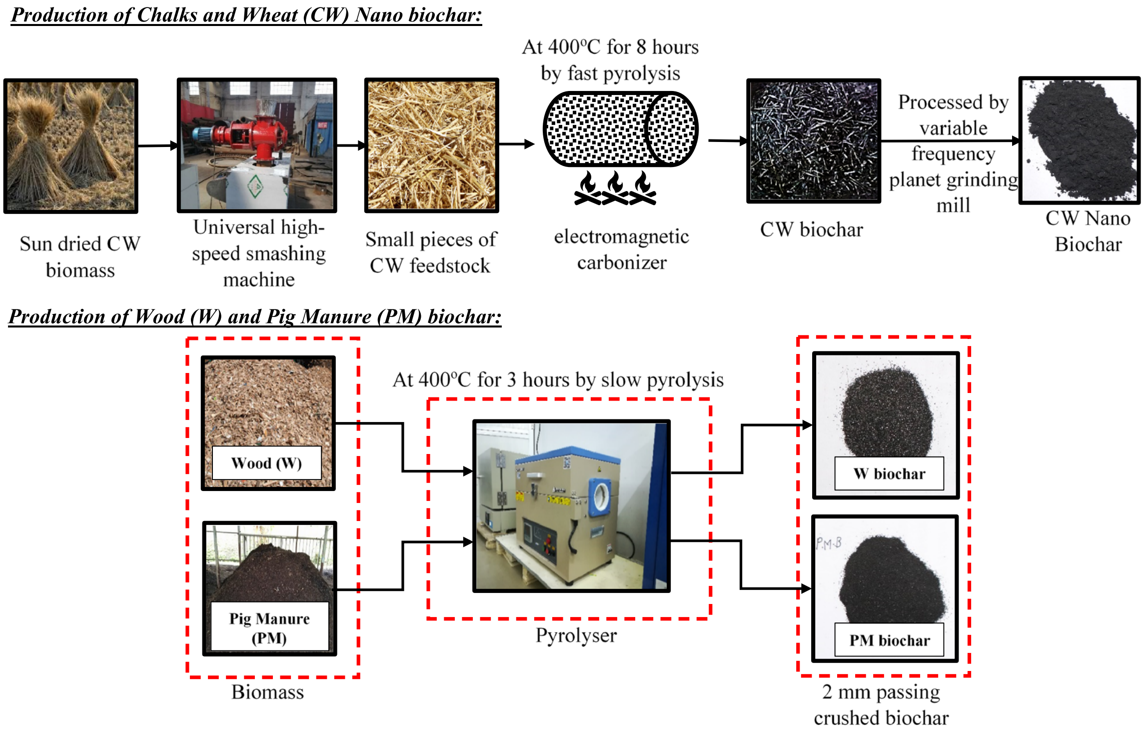


Fig. 1 Production of biochars

the case of CWB, the particles were very finer (100% fine) as it was smashed into ultra-fine powder. Presence of fine particles in biochar influences the crack initiation process and water retention capacity in BAS (Major et al. 2012). CW nano-biochars have 100% fine particles due to ultra-fine powder. Size, shape, and surface characteristics analysis were summarized in Table 3 (Clark 1986; Clogston and Patri 2011). Surface characteristics suggest that all biochars have elliptical structure with the aspect ratio of around 0.6. WB has the highest roughness and abundant surface charges while CWB had the lowest roughness and surface charge among the other biochars. This attributes to production procedure of individual biochar.

2.3 Experimental planning and test setup

In this study, three distinct biochars were used. To investigate the effect of biochar percentage rate, 5% and 10% biochar percentage were selected based on agricultural and geo-environmental applications (Jha et al. 2010; Bordoloi et al.

Table 2 Particle size distribution of wood, pig manure biochar, and bare soil

Sieve size	Particle size distribution (PSD)			
	Bare soil (%)	WB (%)	PMB (%)	CWB (%)
> 4.75 mm	0.2	0.0	0.0	0.0
2.36 mm–4.75 m	18.5	3.1	2.2	0.0
Coarse particles	*18.7*	*3.1*	*2.2*	*0.0*
1.18–2.36 mm	26.4	4.8	3.1	0.0
0.6–1.18 mm	27.8	9.0	10.0	0.0
0.15–0.6 mm	14.0	9.0	17.4	0.0
0.3–0.6 mm	8.3	9.7	23.4	0.0
0.075–0.3 mm	4.5	22.3	23.8	0.0
Medium particles	*81.1*	*54.9*	*77.6*	*0.0*
< 0.075 mm	0.3	42.0	20.2	100
Fine particles	*0.3*	*42.0*	*20.2*	*100*

Italicized entries brief the particle size range and also indicate the overall content of coarse, medium and fine particles

Table 3 Surface properties of biochars

Type	Aspect ratio (%)	Roundness (%)	Roughness (%)	Surface charge ($e^{-6}C/cm^2$)
WB	62.992	54.021	17.018	0.4549
PMB	64.398	52.466	19.289	0.7202
CWB	66.705	57.550	11.193	0.3378

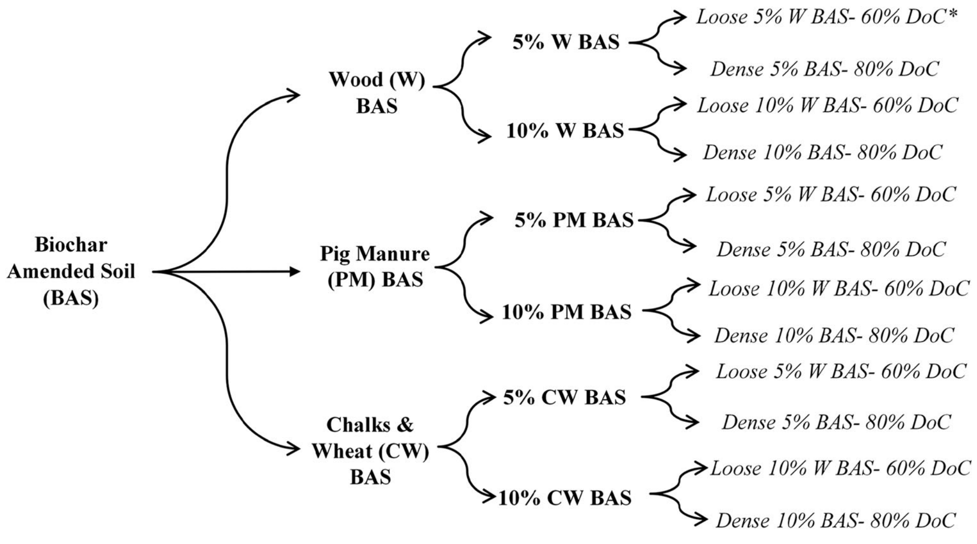
2018b; Sekharan et al. 2019). Two compaction states, 60% and 80% DoC, have been selected to investigate the effect of compaction state on cracks. The detailed experimental plan is shown in Fig. 2. The compacted soil samples were prepared in the glass petri dishes of dimensions 10.3 cm diameter and 1.7 cm height (Fig. 3). W, PM, and CW nano-biochar were mixed with oven dry soil in 5% and 10% biochar weight ratio. The mass of BAS to be compacted was calculated based on DoC of biochar. Soil samples were carefully compacted in three layers using a mechanical compression to maintain uniform density. After preparing the samples, four drying and three wetting periods were alternately simulated. In order to investigate the effect of simulated cycles, each drying-wetting cycle was monitored for 12–15 days drying until there was steady minimal evaporation loss and 5–7 days of wetting such that most cracks were naturally suppressed (An et al. 2018). A minimum of four drying-wetting cycles were adopted as per recommendation given in previous studies on desiccation cracks (Denef et al. 2001; Mikha et al. 2005; Bordoloi et al. 2019). This recommendation was based on cycles required for getting free micro-aggregate and achieving peak crack potential of the composite. High-resolution images in RGB scale with 8-bit depth were captured to monitor the crack for every 24 h. Subsequently, evaporated water of each sample was calculated after imaging of samples.

2.4 Processing of high-resolution images

Raw images were captured using high-resolution camera (*model-MVL-MR2520M-5MP*). During image processing, the five subsequent steps followed are mentioned below (Fig. 3):

1. Uploading raw image in RGB format.
2. RGB image was converted into an 8-bit gray scale image.
3. Thresholding the image to obtain the binary image (contains noise).
4. Refining the image to attain the threshold image without noise.
5. Every pixels of binary images were counted to obtain the CIF.

RGB image was directly converted to 8-bit gray scale with weight of 33.33% for each red, green, and blue color. Many algorithms (like MaxEntropy, mean, MinError, minimum etc.) were tested to obtain the neat and clean cracks in sample. From the noised binary image, noise from the images was reduced/removed using selective median filter that can replace a pixel by the median of the pixels in the surrounding. Literature shows that the ratio between the cracks area of soil surface to the total surface area of the soil sample is known as CIF. Classic definition of CIF is given as (Miller et al. 1998):



* *DoC-Degree of Compaction*

Fig. 2 Experimental matrix for conducted tests

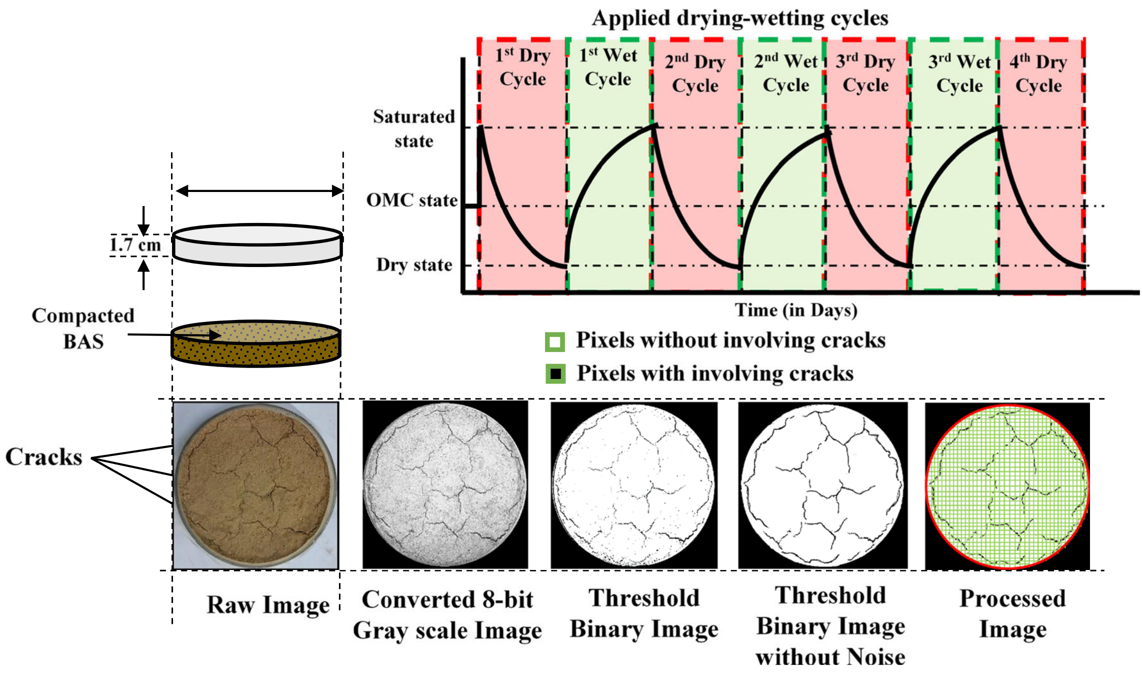


Fig. 3 Experimental set up and process of analyzing the image for crack analysis

$$\text{CIF}\ (\%) = \frac{\text{Crack Area}}{\text{Total area}} \times 100 \tag{1}$$

Based on pixel count, crack intensity factor (CIF) was calculated:

$$\text{CIF}\ (\%) = \frac{\text{Number of pixels within the cracks}}{\text{Total number of pixels in circular dish}} \times 100 \tag{2}$$

For a fair comparison among the various BAS type samples, obtained data, absorbed water content, and CIF were normalized using feature scaling method. Feature scaling brings all the data within the range of 0 to 1 (Gibson and Amies 2001). It is also termed as unity-based normalization. To calculate normalized data, formula is mentioned below (Gibson and Amies 2001):

$$X' = \frac{X - X_{\text{Min}}}{X_{\text{Max}} - X_{\text{Min}}} \tag{3}$$

where

X' normalized data
X original data
X_{Min} minimum value of CIF or absorbed water
X_{Max} maximum value of CIF or absorbed water

3 Result and discussion

Characteristic properties of each biochar have been discussed in Fig. 4 using field emission scanning electron microscope (FE-SEM) and Fourier transform infrared (FTIR) analysis. In the following section, comparative analysis was done for WB, PMB, and CW biochar with respect to retained water (or evaporation rate) and crack propagation. Effect of drying-wetting cycles on evaporation rate has been discussed in detail with varying compaction state and biochar type.

3.1 FE-SEM and FTIR analysis of different types of biochars

FE-SEM and FTIR analyses have been performed to observe the surface morphology of used biochar and available functional groups on the biochar surface. Figure 4 shows the FE-SEM images at 2 K× magnification and FTIR response of three distinct biochars (W, PM, and CW nano-biochar). It was observed that WB has relatively higher number of intra-pores as compared to other biochars. The reason of highly porous structure is the presence of lignocellulosic biopolymers in plant-based biochar (Das and Sarmah 2015). At high temperature, biopolymers (such as cellulose and hemicellulose) present in plant-based feedstock degrades and thereby the honeycomb porous structure is created (Das et al. 2015; Lehmann and Joseph 2015). However, animal-based biochar (PMB) has minimal proportion of lignin, cellulose, or hemicellulose (Fig. 4). Therefore, number of pores in PMB are relatively low (Zhang et al. 2013). In case of CWB, many pores got defaced during the crushing process. Therefore, CWB contains a smaller number of pores than WB (Oleszczuk et al. 2016). Highly porous structure of WB helps soil to store more amount of water compared to other BAS. The

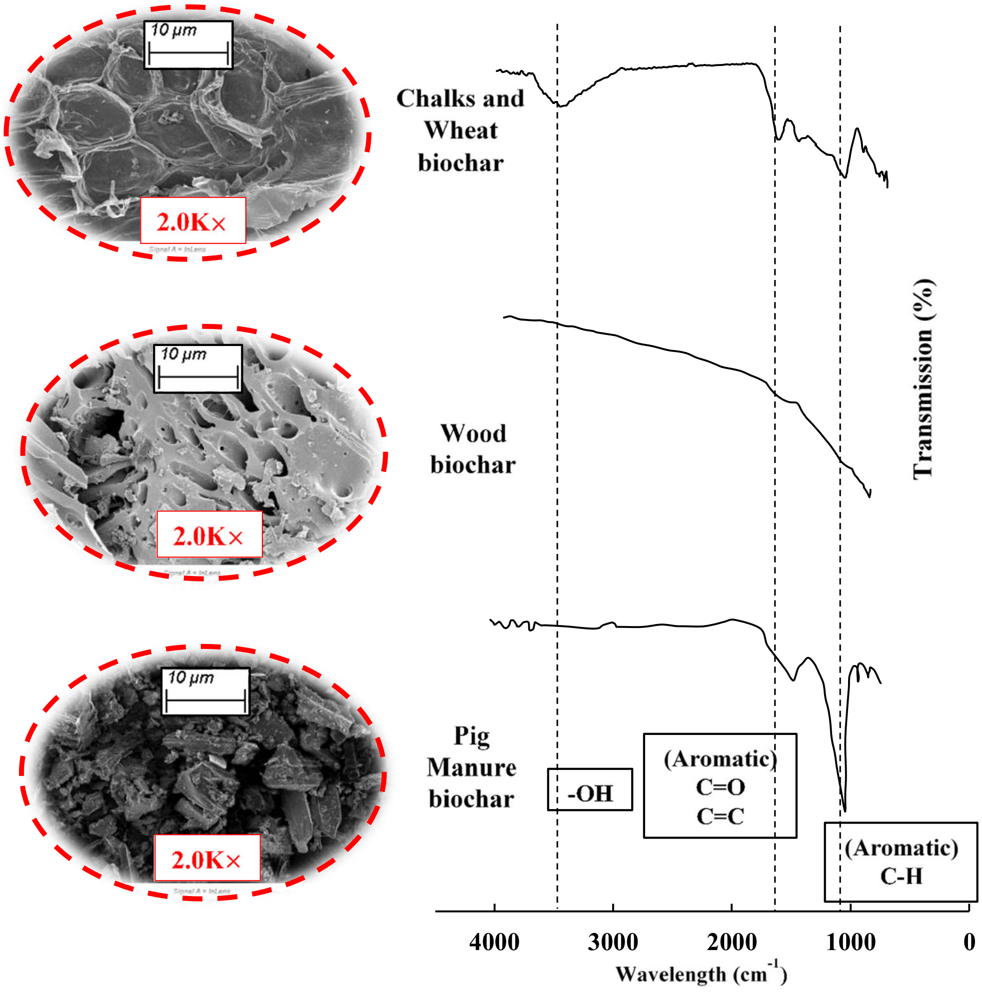


Fig. 4 FE-SEM and FTIR analysis of biochars

detailed explanation is provided in Sect. 3.2 on the water retention capacity of BAS.

Fourier transform infrared (FTIR) analysis responses are represented in Fig. 4. FTIR responses show the relation between percentage transmission of light by molecules with wave number for biochars. Presence of hydroxyl, carboxyl, ketone, aliphatic, and aromatic group affects the hydrophilicity and hydrophobicity of the biochar. Absence of stretching at 3500 cm^{-1} in WB and PMB shows the unavailability of hydroxyl group (–OH) (Smidt and Meissl 2007; Smith 2011). In this study, used WB and PMB show hydrophobic behavior (Lehmann and Joseph 2015). CW shows a stretching at 3500 cm^{-1} that confirm the presence of hydroxyl (–OH) group (Smidt and Meissl 2007). Presence of hydroxyl group makes the CWB hydrophilic in nature (Lehmann and Joseph 2015). The reason for having hydroxyl (–OH) group must be due to high specific surface area of CWB and production procedure. Having active hydroxyl group at surface that can be used to trap the containment in soil and water (Uchimiya et al. 2011).

3.2 Effect of biochar type and compaction state on retained water under drying-wetting cycles

Figures 5 and 6 represent the plot between normalized retained water and time for three biochars WB, PMB, and CWB at 0%, 5%, and 10% biochar percentage. The results show that presence of biochar can significantly vary the retained water in BAS. From the obtained results, plant-based WB showed the highest water retention among other biochars used in this study, i.e., WB increases the water-holding capacity of soil compared to CWB and PMB. It can be attributed by the porous honeycomb structure of WB, which assists WB to store more water in intra-pores (Das and Sarmah. 2015; Ni et al. 2018). Meanwhile, the other two biochars did not possess the same property due to the absence of lignin materials in PM feedstock (Das and Sarmah 2015) and the defacement of CW biochar during production (Yeling 2004). In addition, surface characteristics (Table 3) of biochars suggest that CWB shows poor performance in retaining water because it has low surface roughness and weak surface

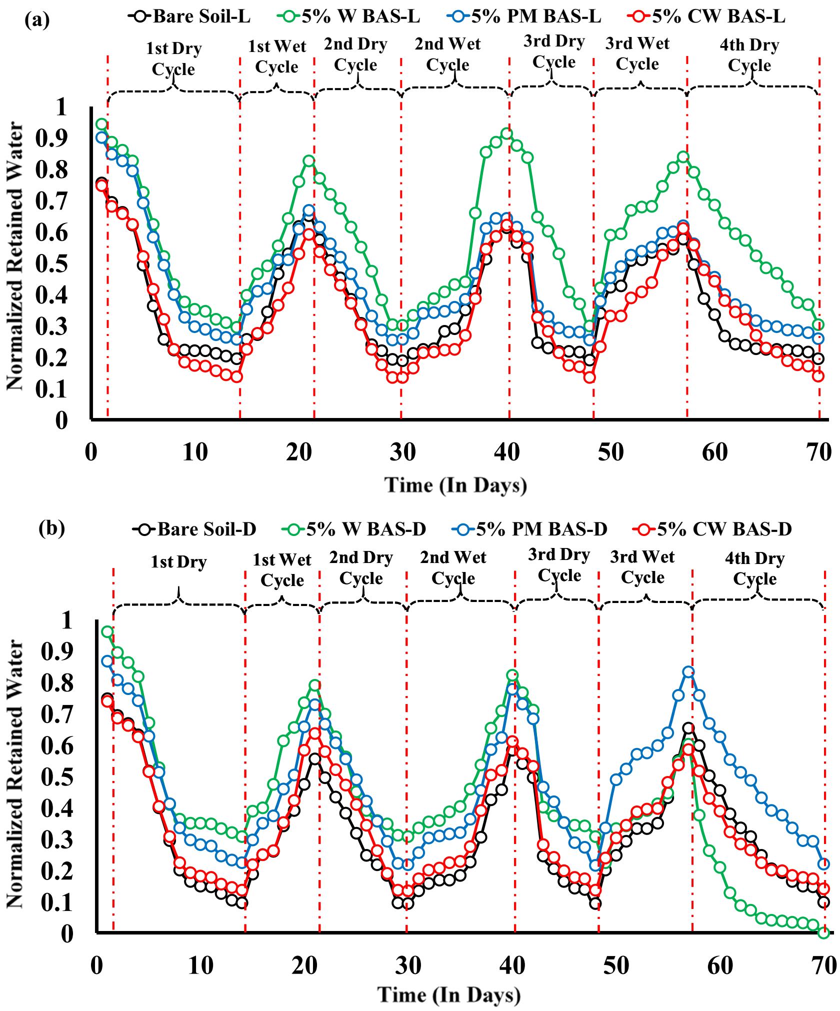


Fig. 5 Normalized retained water for 5% BAS in loose compaction state

charges. WB shows high intra pore structure with irregular particle shape which helps the W BAS in retaining more water (Liu et al. 2017). Figures 5 and 6 also represent that drying-wetting cycles of BAS report a marked change in water retention. The retained water during the first drying cycle by all BAS is higher than the second, third, and fourth cycles. Water-holding capacity or retained water by BAS decreases due to initiation of desiccation cracks and increased water evaporation through existing cracks. Water retention of BAS also depends on the compaction state of BAS.

Figures 6 and 7 reveal that as the biochar percentage increases from 0 to 10%, water retained by BAS also increases for loosely compacted samples. However, in the case of highly compacted soil, with the increasing biochar percentage from 5 to 10%, water retention decreases. This is majorly attributed due to the availability of less void spaces in bare soil and BAS due to high compaction (Joseph et al. 2013; Chia et al. 2015). Therefore, the available space for restoring water reduces and thereby the water-holding capacity of soil reduces as compared to loose compacted soil (Lemon 1956; Ball 2001).

3.3 Effect of biochar type and compaction state on cracking under drying-wetting cycles

Variation of normalized CIF with time for loose and dense compacted state of BAS has been illustrated in Figs. 8 and 9. The results from the experiments for loose state of BAS at 5% and 10% biochar percentage are shown in Fig. 8. Plant-based WB shows the lowest CIF among the biochars used in this study. With the increasing biochar percentage from 0 to 10%, cracks in specimen reduce for WB in loose state. Highly porous structure of WB assists the soil to retain more water. In the presence of high retained water, suction developed in BAS is relatively low. Surface morphology of biochar particles affect the crack development in BAS. The roughness of biochar particles increases the soil internal friction which restricts the crack formation and shrinkage in BAS. In the presence of high retained water, hydrogen bond and van der Waals' force resist the development of cracks (Reza et al. 2012). Therefore, formation of cracks reduces in case of W BAS. Among all BAS, PMB, and CWB, amended soils show the highest value of CIF at 10% biochar percentage in loose state of soil. This can be

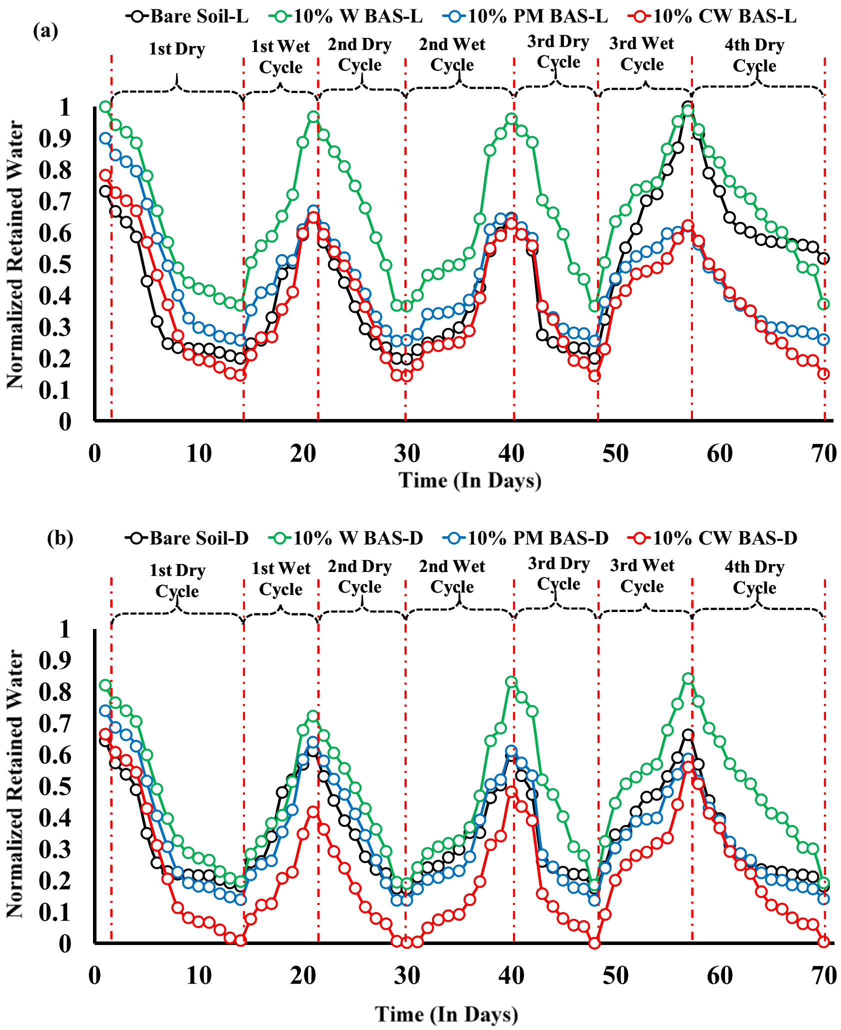


Fig. 6 Normalized retained water for 10% BAS in dense compaction state

likely due to lower porous structure of CWB and absence of biopolymer materials in PMB.

In case of highly dense compacted BAS, mixing of WB in soil represent better performance for reducing the cracks in soil. As the biochar percentage increases from 0 to 10%, CIF for densely compacted BAS reduced irrespective of type of biochar. Furthermore, PMB and CWB showed similar results with respect to induced cracks. (Fig. 9). At 5% biochar percentage, CIF value of specimen decreases for WB and PMB in dense soil. However, addition of CWB had no significant effect on CIF with respect to compaction state of specimen at low biochar percentage, i.e., 5%. It can be observed from Figs. 8b and 9b that the CIF reduces rapidly as we increase the biochar percentage up to 10% during dry cycles. It can be attributed to less evaporation of water and high water-holding capacity of BAS in dense state (Yu et al. 2013). Soil specimen absorbs heat energy from the atmosphere, which is used in the evaporation of water from the soil surface of specimen. The evaporation also depends on the pore distribution in addition to temperature and relative humidity. Heterogeneous pore distribution results in random evaporation rate on the soil surface (Lakshmikantha et al. 2009). Various biochar types such as plant-based, animal-based, and nano-structural-based biochar show distinct evaporation rate due to non-uniform pore structure and random pore distributions. In nano-CWB, capillary effect is high due to small void size and availability of water for evaporation rate at the surface is also relatively higher. However, plant-based WB has larger particles and high inner pores that help to retain more water. Furthermore, capillary effect is minimal for larger particles due larger pore size. Hence, water availability at the surface for WB is less than PMB and CWB amended soils.

3.4 Discussion on different mechanisms of treatment for suppressing desiccation cracks

To minimize the formation of cracks, in addition to biochar, other treatment materials such as waste plant fiber and vegetation have also been adopted. Figure 10 represents the CIF vs biochar percentage. The idea is to explore and understand the

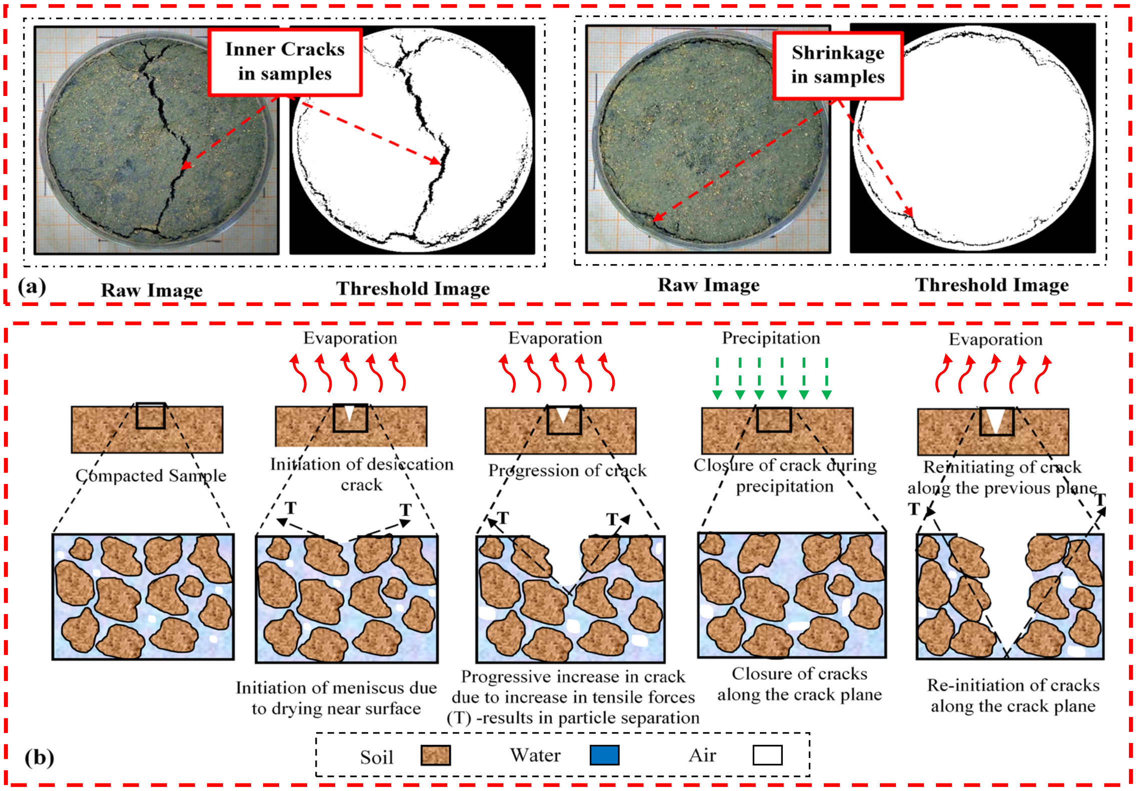


Fig. 7 Crack pattern and formation mechanism for specimens

performance of different treatment techniques (addition biochar, fiber, and vegetation) in suppression of the cracks. Bordoloi et al. (2018a, b) investigated the cracks in soil mixed with grass species and WH biochar. The maximum CIF for bare soil and vegetated soil was found to be in the range of 1.69–2.6% and 1.48–2.0%, respectively (Bordoloi et al. 2018b). It is reported that the cracks in bare soil are higher than the vegetated soils. Certainly, root growth also restricts the propagation of cracks and reinforces the soil beneath the soil surface (Tang et al. 2007; Zhou et al. 2009; Loades et al. 2010). However, some literature studies report contradictory effects of vegetation on desiccation cracks (Li et al. 2016; Gadi et al. 2018). In the case of vegetated soil, suction induced within the soil increased due to plant evapotranspiration rate. This effect from plant evapotranspiration can overcome the root bridge effect (Zhou et al. 2009) and hence can cause vegetated soil to induce more cracks than bare soil. This is more likely to happen during younger age of plant seedlings (Gadi et al. 2018), when roots have lower biomass and hence overall low tensile resistance. Also, the plant species used in case of Gadi et al. (2018) is a vegetative crop, where the roots are relatively less dense than that of the vegetation grown on engineered slopes. The type of vegetation (Garg and Ng 2015) can also influence behavior of soil cracking, which needs further investigation. As compared to above treatments, biochars were able to reduce cracks irrespective of their type (WHB, WB, PMB, CWB etc.) and amendment percentages (0%, 2%, 5%, 10%, 15% etc.). The mechanism for suppression of cracking was mainly due to high water retention in porous structure of biochar (Bordoloi et al. 2018a, b). The mechanism was different from that of vegetation and fibers, where tensile strength (mechanical) provides resistance to crack development.

Bordoloi et al. (2018a) obtained the CIF% for WH BAS and reported that with the increasing biochar percentage from 0 to 15%, CIF% decreases from 7.4 to 2.7% for moderate compacted soil. In this study, densely compacted BAS shows the high resistance towards crack propagation. In densely compacted soil, maximum CIF% can be reduced from 3.9 to 0.4% for W BAS, 3.9 to 1.7% for PM BAS, 3.9 to 1.6% for CW BAS, and 7.4 to 3.3% for WH BAS (Bordoloi et al. 2018a). During the evaporation of water and initiation of cracks, an air water interface is developed on the BAS surface in unsaturated phase. Due to cohesive nature of soil (Cordero et al. 2017), soil contraction begins, and propagation of crack is initiated. Furthermore, lowest contraction in W BAS is due to its high trace of porous honeycomb structure that helps the BAS to retain more water (Das and Sarmah 2015). For further understanding, % CIF reduction has been plotted with biochar percentage (Fig. 10). It was observed that addition of any biochar used in this study at 10% biochar percentage performed even better than the vegetated soil used by Bordoloi et al. (2018b) which shows the total reduction in CIF is 23.1%. As biochar percentage increases, CIF reduction (%) increases from 23.4 to

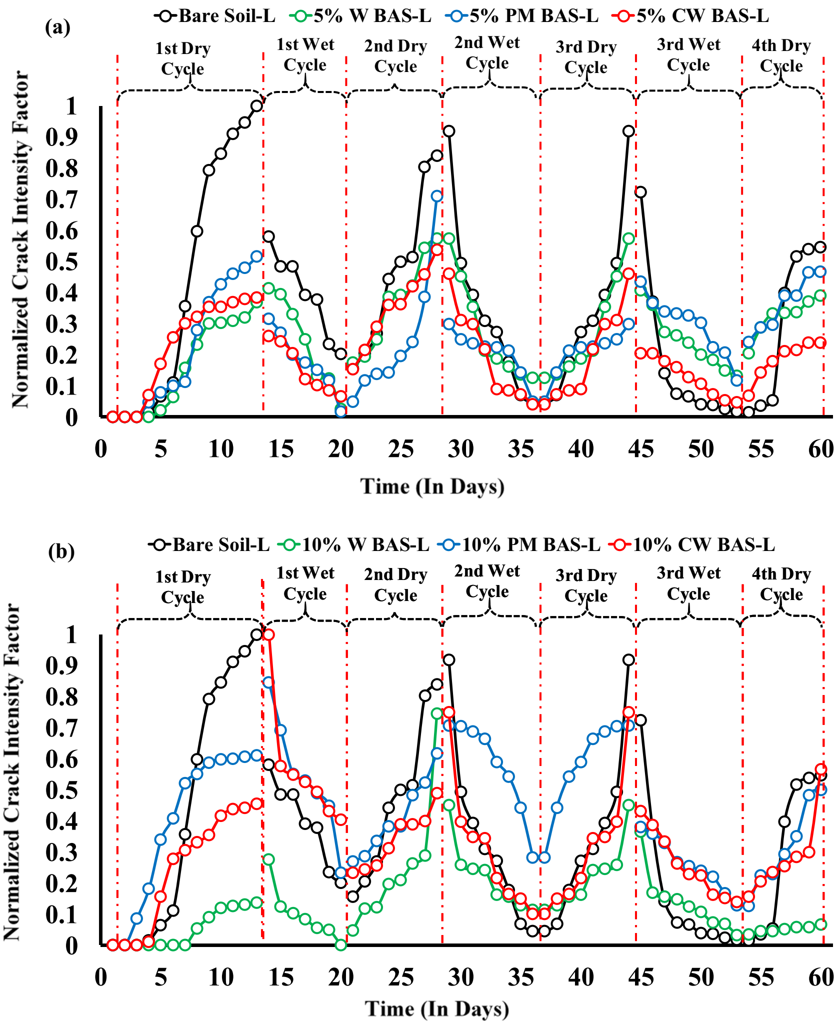


Fig. 8 Normalized crack intensity factor (CIF) in loose state for 5% BAS and 10% BAS

67.6% in previous study (Bordoloi et al. 2018a). In the current study, performance of densely compacted soil seems much better than loosely compacted soil and vegetated soils (Fig. 11).

4 Conclusion

In this study, two conventional (i.e., wood biochar (WB) and pig manure (PMB) biochars) and one novel nano-biochars (CWB) were produced. The effect of biochar type, biochar percentage, and compaction state of BAS on retained water and cracks has been reported for four drying and three wetting cycles. The following conclusion were inferred based on outcomes and discussion in this study:

1. Presence of biochar can reduce crack formation and with the increasing biochar percentage, CIF reduces significantly. WB was able to resist the cracking more efficiently than PMB and CWB. Evaporation rate was found to be minimal for plant-based BAS at 10% biochar percentage.
2. Dense state of soil at high biochar content (i.e., 10%) was quite effective in reducing evaporation rate and progression of cracks. In agricultural applications, loose soil can be used only with low biochar percentage (< 5%) for effectively reducing the formation of cracks. Alternatively, plant-based biochar can also be utilized.
3. Cracks cannot be fully recovered after a certain value of crack intensity factor (CIF) even under wetting cycles. However, some proportion of cracks re-covered near the saturation state in both loose and dense compaction states.

CWB does not show a good performance (due to lower porosity) in restoring water and reducing the formation of cracks like WB and PMB. However, CWB can be used for trapping containments in soil and water based on available literatures. The current study represents that plant- and animal-based biochars can be used as suitable cover material in geo-environmental applications considering the influence of biochar type, compaction state of BAS, and adopted drying-wetting cycle pattern. Future work can be

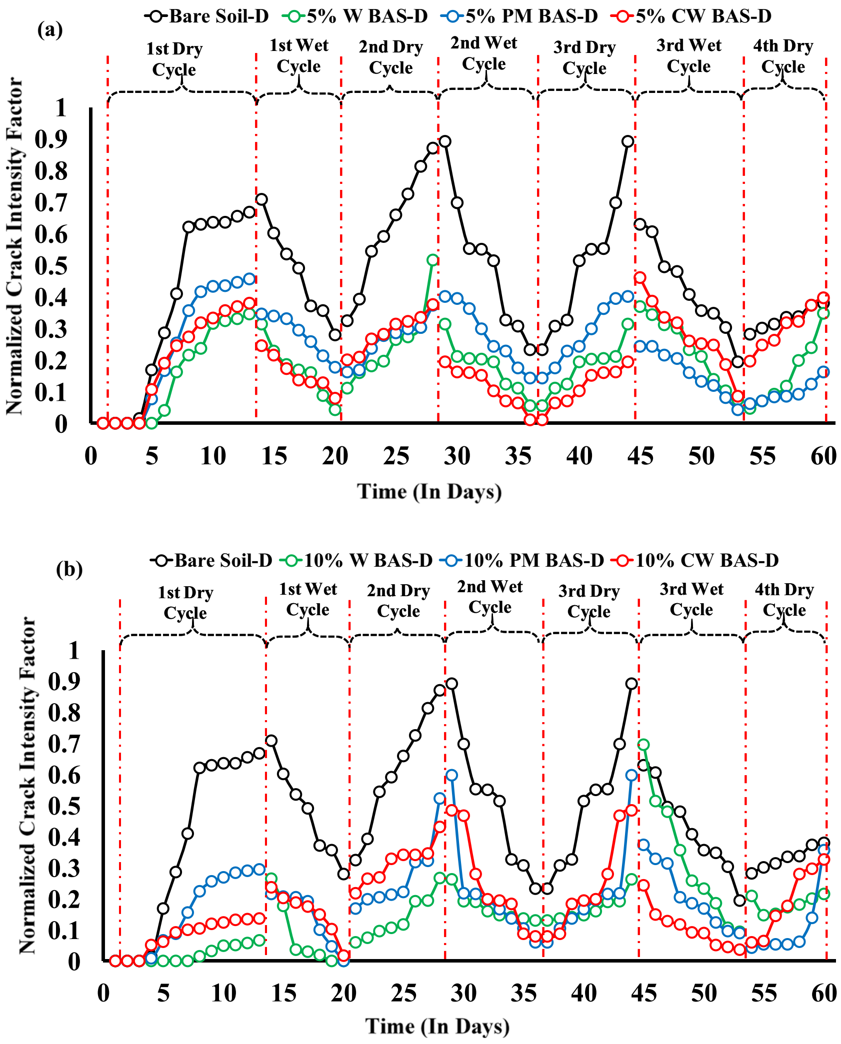


Fig. 9 Normalized crack intensity factor (CIF) in loose state for 5% BAS and 10% BAS

done to consider computational intelligence methods (Jiang et al. 2019; Liu et al. 2017) for development of theoretical models and also understanding relative significance of input parameters. These models can be integrated into experimental process for monitoring and improving its efficacy.

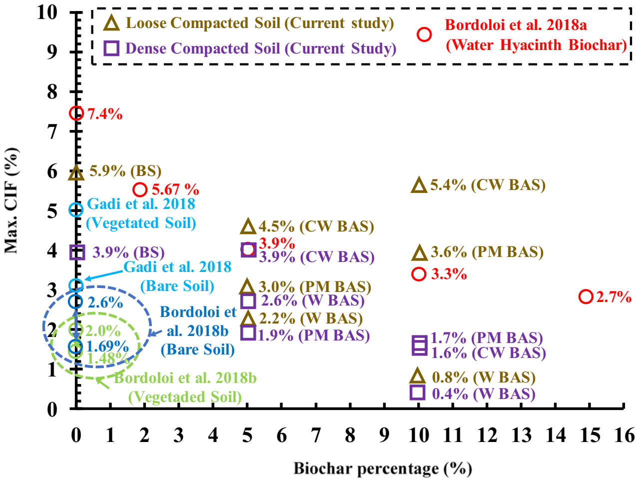


Fig. 10 Comparison between cracks data developed from various mechanism (Bordoloi et al. 2018a, b and Gadi et al. 2018)

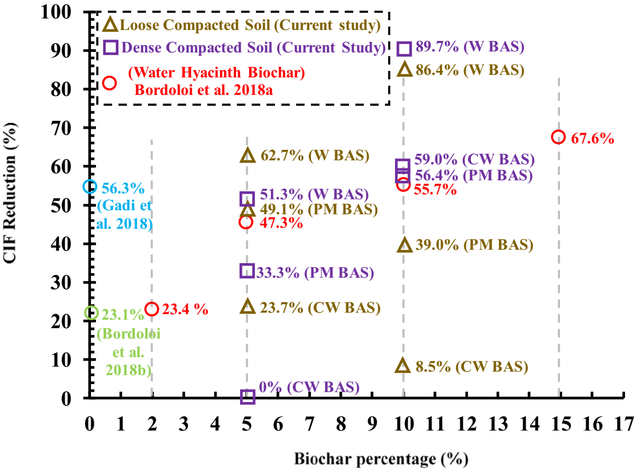


Fig. 11 CIF reduction (%) data developed from various mechanism (Bordoloi et al. 2018a, b and Gadi et al. 2018)

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