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Comparison of various sustainable amendments on soil cracking in semi-arid regions

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ABSTRACT

Soil desiccation is an important process that happens mainly in semi-arid regions especially in Central Asia. Soil desiccation leads to higher loss of moisture at shallower depths and also deeper penetration of water, which ultimately reduces water availability and hence impacts the growth of plants for the application of agriculture and green infrastructures. Therefore, minimizing soil desiccation will help maintain higher water availability for plants for agricultural productivity and green infrastructure in Central Asian Region. In literature, various amendments such as natural fibers, cementation, lime, vegetation and biochar have been used to suppress cracking of soil. There is rarely any study that analyses and compares mechanism of crack suppression among the above-mentioned methods. The objective of this study is to explore various sustainable methods of minimizing soil desiccation and compare their mechanisms. Further, the aim is to analyse the feasibility of these methods by revealing their advantages and disadvantages. In order to achieve this objective, 1-D columns were prepared with control soil and amended soil (with fibers, vegetation and biochar). The review also provides insights into their mechanism of suppression of soil cracking by proposing a new factor (i.e., normalized CIF). Based on the proposed factor, the efficiency of biochar and fiber amendments are higher than that of vegetation. Vegetation may or may not have positive impact on cracking of soil depending on their shoot length. Among various amendments, wood biochar (10% content) and coir fiber (at 0.75 % content) seems to have highest efficiency in reducing cracking in soil. Overall, the study aims to develop preliminary guidelines suppressing soil desiccation in semi-arid regions such as Central Asia.

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1. Introduction

Amid rising concerns about carbon sequestration and climate change, there's a growing trend toward exploring sustainable methods for designing and developing green infrastructure and agriculture productivity that includes green roofs, biofiltration units, urban lawns, plant growth, and crop yield (Matthews et al., 2015; Saha et al., 2020; Rattan et al., 2023). This shift aims to create eco-friendly solutions that mitigate environmental impact while enhancing urban resilience and promoting biodiversity. The main idea of using sustainable approaches is to ensure minimal exploitation of resources while developing as well as maintaining green infrastructure and agriculture productivity. This is particularly important for Central Asian region, which is particularly rich in natural resources. Considering the importance of Central Asian region, is therefore necessary to explore various sustainable means such as use of biomaterials (fibers, biochar etc.) (Bordoloi et al., 2016; Garg et al., 2020) and vegetation for enhancing durability and performance of green infrastructure and agriculture productivity (Rattan et al., 2024).

Many studies have been conducted in literature that analyses use of synthetic materials such as fibers, cement and soil nailing for mitigating problems of cracking in green infrastructure (Dhakal et al., 2016; Roque et al., 2021). Cracks in ground occurs mainly under drying-wetting cycles due to tensile stresses (Tang et al., 2020). In addition, the formation of cracking and its pattern also depends on the minerology present in the soil (Vogel et al., 2005). Most of studies in literature have focused on use of cementation, fly ash, synthetic fibers for minimizing cracking soil (Hejazi et al., 2012; Sharma, 2018; Tjdini et al., 2018; Sharma 2018; Sengul et al., 2023). On the other hand, recent literature mainly explored sustainable materials and fiber for the management of concrete structures (Khitab et al., 2021; Maljaee et al., 2021; Dadkaha and Tulliani, 2022). On the contrary, lesser studies have focused on the use of sustainable materials such as fibers, biochar, and vegetation to minimize the cracking of soil (Gadi et al., 2017; Bordoloi et al., 2018 & 2019; Garg et al., 2019; Infurna et al., 2023). Further, there is also a lack of systematic studies, which show a comparison of the effects of different sustainable materials on the cracking of soil for various applications, including green infrastructure and agricultural productivity. These sustainable materials can influence soil-water-atmospheric interaction in a different mechanism thus affecting water retention and overall crack suppression efficiency. Most of these materials also induce changes in soil water retention characteristics (Garg et al., 2019; Rattan et al., 2022), that needs to be analysed in conjunction with their crack suppression characteristics.

This study aims to examine how sustainable materials like fiber, biochar, and vegetation impact soil cracking and water retention. By exploring the mechanisms behind these amendments (fiber, biochar, and vegetation), to identify their effectiveness and suitability for various climates and soils in Central Asia. This review will provide valuable insights into sustainable solutions for soil management in the region. The literature that explores effects of these sustainable materials on cracking of soil was reviewed with new insights. Cracking was measured in terms of crack intensity factor (CIF). CIF is defined as the ratio of total surface area of cracks to the total soil surface area. In this study, a new parameter, normalized CIF is proposed. Normalized CIF is defined as the ratio between CIF of amended soil to bare soil for a given testing condition. This is done to minimize fluctuations caused by difference in testing conditions across several studies. Further, the normalized CIF can indicate the overall efficiency of a sustainable amendment in suppressing cracking in soil.

2. Materials and Methodology

The literature from articles associated with crack suppression of soil using fibers (Bordoloi et al. 2018), biochar (Bordoloi et al., 2018; Kumar et al., 2020) and vegetation (Gadi et al., 2017) were analysed. Table I summarizes the testing condition (greenhouse or climate-controlled chamber) as well as materials (soil, biochar and vegetation) used in their studies. Most of the studies were conducted in a greenhouse to minimize any effects of natural rainfall and other climate fluctuations. Study by Kumar et al. (2020) for investigating effects of various biochars on water retention and cracking was performed in a climate-controlled chamber while other studies (Gadi et al., 2017; Bordoloi et al., 2018; Bordoloi et al. 2019) were conducted in a green house. The purpose of using climate control chamber was to control relative humidity and temperature so as to control matric suction via kelvin's equation (Fredlund and Rahardjo, 1993). As observed from the Table I, wide variety of soil (inorganic silt, clayey silt, sandy clay and silty sand) and feedstock type (wood biochar, Chalk and Wheat Biochar and Pig manure) have been used. Zhang et al. (2022) explored the development of potential of cropland in Central Asia. In their study, they attempted to evaluate the influence of various factors such as Coir, Jute and Water hyacinth were mainly adapted in form of natural fibers for evaluating their potential in suppressing cracking in soils (Bordoloi et al., 2019). It should be noticed that water hyacinth is most commonly adapted for producing either fiber or biochar. This is due to its availability in many water bodies present in Asia where the studies were conducted. For Central Asian region, other feedstocks type including that from animal waste may be also useful owing to presence of widespread farming and nomad population.

Table II summarizes the amendment ratio of biochar and fibers that were considered in previous studies. It could be noticed that these amendments varied from 0 to 10 % in most of the studies except for one case (Bordoloi et al., 2018), where 15 % biochar content was considered.

Table I. Summary of materials adopted in selected literature.

Literatures	Methodology		Amendment type					
	Greenhouse	Climate control	Vegetation	Fiber	Biochar	Soil type	Fiber/ Biochar type	Pyrolysis temperature (°C)
Gadi et al. (2017)	√	-	√	-	-	Inorganic silt	-	-
Bordoloi et al. (2018)	√	-	-	-	√	Sandy-clay	Water Hyacinth	300 -350
Bordoloi et al. (2019)	√	-	-	√	-	Clayey silt	Jute, Coir, Water Hyacinth	-
Kumar et al. (2020)	-	√	-	-	√	Silty Sand	CW B, PM B, W B	300, 600

Table II. Amendment ratio of biochar or fibers used in literature. Shoot length is used for representing vegetation as an amendment

Study	Amendment ratio		
	Vegetation	Fiber	Biochar
Gadi et al. (2017)	Shoot Length (0 to 800 mm)	-	-
Bordoloi et al. (2018)	-	0.75 %	-
Bordoloi et al. (2019)	-	-	0 %, 2 %, 5 %, 10 % and 15 %
Kumar et al. (2020)	-	-	0 % 5 % and 10 %

For production of biochar using pyrolysis process, temperature range of 300 °C -350 °C (Bordoloi et al., 2018) and 350 °C -400 °C (Garg et al., 2019) was adopted. Whereas, in study by Kumar et al. (2020), pyrolysis temperature of 400 °C was adapted for production of biochar from different feedstocks such as pig manure, wood and chalk and wheat. It should be noted that the pyrolysis temperature is likely to affect physio-chemical properties of biochar. Generally, higher pyrolysis temperature will lead to larger porosity with reduced functionality in biochar. Whereas lower pyrolysis temperature is likely to have lower porosity but with enhanced functionality (hydrophobic and hydrophilic functional groups). This in turn may influence the water retention and crack suppression efficiency of biochar (Wani et al., 2021).

3. Testing procedures

All tests were carried out in a clear box with apertures at opposing ends. Soil samples were compacted in a PVC cylindrical column (300 mm diameter, 250 mm height) that was selected based on the representative elementary diameter (137.5 mm) required to research crack development. The column had a perforated base plate with filter paper to limit soil loss while enabling water drainage. A small layer of grease reduced soil-PVC friction during compaction. The soil was oven-dried, and amendment, which were also air-dried, were mixed by mass. To avoid lumps, the soil amendment mixture was sprayed with distilled water. To prevent salt interference in suction measurements, distilled water was utilized regularly. Each compacted sample was placed in a clear container, exposed to the natural environment, and irrigated under controlled conditions. A sprinkler system installed on top of the soil columns provided precise irrigation during the monitoring period, resulting in accurate and dependable data for the study. the detailed explained were given in the previous literature (Bordoloi et al., 2018 & 2019; Garg et al., 2019).

4. Results and Discussion

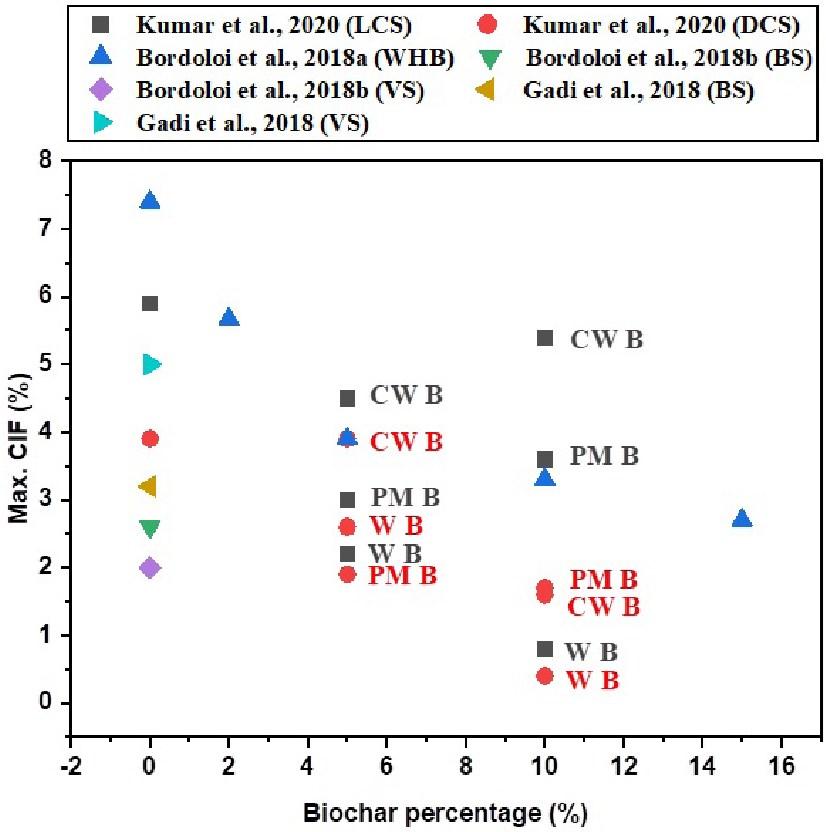

Figure 1. Comparison of the CIF with different soil amendment from previous literatures

Note*= LSC: loosely compacted soil, DCS: dense compacted soil, WHB: Water hyacinth biochar, BS: bare soil, VS: vegetated soil, CW B: Chalks and Wheat based biochar, PM B: Pig manure based biochar, W B: Wood based biochar

Various treatment materials, including biochar, waste plant fiber, and vegetation, have been utilized to reduce the development of cracks. The CIF versus biochar percentage is depicted in Figure 1, while Table III provides a summary of the measured CIF as well as normalized CIF in both bare soil and amended soils. The objective of this study is to comprehend the efficacy of several treatment methodologies, including the incorporation of biochar, fiber, and vegetation, in suppressing crack propagation. The cracks in soil mixed with grass species and WH biochar was examined by Bordoloi et al. (2018a, b). According to Bordoloi et al. (2018b), the highest CIF observed for bare soil was 2.6%, whereas for vegetated soil, it was 2.0%. According to reports, the cracks in bare soil are greater compared to vegetated soils. Root growth has a crucial role in limiting the spread of cracks and strengthening the underlying soil surface (Tang et al., 2007; Zhou et al., 2009; Loades et al., 2010). Nevertheless, some literature investigations have presented conflicting findings about the impact of vegetation on desiccation cracks (Li et al., 2016; Gadi et al., 2018). According to the findings of Gadi et al. (2017), the CIF values noticed in vegetated soil were comparatively greater in comparison to bare soil. In the case of vegetated soil, suction induced within the soil can be attributed to the plant evapotranspiration. The phenomenon of plant evapotranspiration has the potential to counteract the root bridge effect, as demonstrated by Zhou et al. (2009). Consequently, vegetated soil may exhibit a greater tendency for crack formation compared to bare soil. This phenomenon is more likely to occur during the early stages of plant seedling development (Gadi et al., 2018) since the roots exhibit reduced biomass and, hence, possess low tensile resistance. In the case of Gadi et al. (2018), the plant species chosen is a vegetative crop with roots that are less dense compared to the vegetation growing on engineered slopes. The behavior of soil cracking can also be influenced by the type of plants (Garg and Ng, 2015). Furthermore, Gadi et al. (2017) found that the CIF exhibits a linear relationship with shoot length until reaching a threshold of 400 mm. Upon reaching a shoot length of 400 mm, there was no visible increase in CIF corresponding to further ageing of plants.

Bordoloi et al. (2018a) obtained the CIF% for water hyacinth biochar, which was observed a decrease in CIF% from 7.4% to 2.7% for moderately compacted soil as the biochar percentage increased from 0% to 15%. The addition of water hyacinth biochar at a concentration of 5%, results in a 50% reduction in the peak CIF compared to BS. The reduction in surface cracks can be analyzed from two perspectives. Initially, because of the higher water retention capacity of biochar composites compared to BS, the occurrence of cracking will be reduced as the amount of air in the three-phase medium will be lower than BS. Furthermore, while the addition of biochar enhances the finer composition of the soil, these particles exhibit lower cohesiveness compared to BS particles.

Bordoloi et al. (2019) found that the soil reinforced with Coir fiber had the lowest CIF, followed by soil reinforced with water hyacinth and jute. The presence of fibers in soil has been found to decrease its cracking potential through two mechanisms: firstly, by activating the tensile strength of the interlocked fiber as a result of deformation, and secondly, by enhancing the friction at the interface between the soil and the fiber (Tanget al., 2012; Bordoloi et al., 2017a). Coir exhibited the highest capacity for mitigating crack formation due to its multifilament nature, which enables a greater number of fibers to concurrently exert their tensile strength over a crack plane. While coir fiber exhibits lower tensile strength compared to jute and WH, it possesses a greater lignin content, resulting in a rougher surface (Bordoloi et al., 2017a,b). This characteristic contributes to increased friction at the soil-fiber interface.

Kumar et al., 2020 found that biochar was effective in reducing cracks, regardless of the kind of biochar (WB, PMB and CWB) and the percentage of amendment (0%, 5%, 15%, etc.), when compared to the aforementioned treatments. The primary cause of cracking suppression can be attributed to the significant water retention inside the porous structure of biochar, as demonstrated by Bordoloi et al. (2018a, b). The technique employed in this case differed from that of vegetation and fibers, as it relied on mechanical tensile strength to prevent crack formation. It is reported that the densely compacted biochar-amended soil (BAS) exhibits a notable resistance to crack propagation. In densely compacted soil, the maximum CIF% can be decreased from 3.9% to 0.4% for Wood Biochar amended soil, 3.9% to 1.7% for Pig manure biochar amended soil, 3.9% to 1.6% for Chalk and wheat BAS.

As observed from Table III, normalized CIF was usually less than 1 for soils amended with fibers and biochars whereas, it is equal (during initial stage of shoot length less than 127 mm; Gadi et al., 2017) or more than 1 for vegetated soil. This is because vegetation evapotranspiration induced soil suction induces cracking in soil at a much higher rate for higher shoot lengths. For shoot lengths smaller than 127 mm, the root reinforcement effect tends to be higher than that of evapotranspiration induced suction. This implies that vegetation may have positive or negative impact on the cracking of soils depending on its growth stage. On the other hand, both fibers and biochar consistently generally possesses normalized CIF lower than 1 for most of the amendment ratios. It indicates that the consistency of biochar and fibers is more in terms of reducing cracking in soils as compared to that of vegetation. It should be also noted that despite the higher efficiency of biochar in reducing cracking of soil, it may also have negative impact on strength of soil (Wani et al., 2021). Among biochar and fiber amended soils, the lowest normalized CIF corresponds to amendment using wood biochar at 10 % ratio. Highest normalized CIF corresponds to soil amended with 2 % biochar produced from water hyacinth. The Table III results indicates that 10 % biochar content is most optimum in reducing cracking among biochar amended soils. However, among fiber amended soils, coir (at 0.75 % content) have almost similar efficiency as that of wood biochar at 10 % ratio. Coir with 0.75 % have highest efficiency in reducing crack followed by water hyacinth and jute. The results imply that for Central Asian region, coir based raw materials can be very useful in application for remediation of soil that undergoes cracking.

The comprehensive analysis of crack propagation with various soil amendments, including vegetation, fiber, and biochar, is compiled in Table IV. It provides insights into the influence of different materials on the crack intensity factor (CIF). Through this summary, it becomes evident that biochar, particularly those with more than 10% concentration, holds significant potential in reducing soil cracks and improving soil properties. Overall, the data summarized in Table IV highlights biochar's potential as a promising soil amendment for crack reduction, emphasizing its role in mitigating soil degradation and fostering sustainable land management practices.

Table III. Summary of measured crack intensity factor (CIF) in bare soil and amended soils. Their corresponding normalized CIF (ratio of CIF of amended soil and bare soil) is also shown.

	Bare soil			Amended soil			Normalized CIF		
Literatures	Min. CIF	Max. CIF	Mean CIF	Min. CIF	Max. CIF	Mean CIF	Min. CIF	Max. CIF	Mean CIF
Gadi et al. (2017) (127 mm shoot length)	0.93	0.93	0.93	0.9	0.9	0.9	1	1	1
Gadi et al. (2017) (800 mm shoot length)	0.93	3.22	2.075	0.9	5	2.95	1	1.55	1.42
Bordoloi et al. (2018) (2% content)	0	7	3.5	0	5.5	2.25	-	0.78	0.64
Bordoloi et al. (2018) (5 % content)	0	7	3.5	0	4	2	-	0.57	0.57
Bordoloi et al. (2019) (10 %)	0	7	3.5	0	3.3	1.65	-	0.47	0.47
Bordoloi et al. (2019) (15 %)	0	7	3.5	0	2.8	1.4	-	0.4	0.4
Bordoloi et al. (2019) (0.75 %), (Jute)	0	7.2	3.6	0	3.3	1.65	-	0.46	0.46
Bordoloi et al. (2019) (0.75 %), (Coir)	0	7.2	3.6	0	1.27	0.63	-	0.17	0.17

Table III. Cont.

Bordoloi et al. (2019) (0.75 %), (Water hyacinth)	0	7.2	3.6	0	3.18	1.59	-	0.44	0.44
Kumar et al. (2020) (5 %) -chalk and wheat biochar	0	3.9	1.95	0	3.9	1.95	-	1	1
Kumar et al. (2020) (10 %) -Chalk and wheat biochar	0	3.9	1.95	0	1.6	0.8	-	0.41	0.41
Kumar et al. (2020) (5 %) -Pig Manure biochar	0	3.9	1.95	0	1.9	0.95	-	0.48	0.48
Kumar et al. (2020) (10 %) -Pig Manure biochar	0	3.9	1.95	0	1.7	0.85	-	0.43	0.43
Kumar et al. (2020) (5 %) -Wood biochar	0	3.9	1.95	0	2.6	1.3	-	0.66	0.66
Kumar et al. (2020) (10 %) -Wood biochar	0	3.9	1.95	0	0.4	0.2	-	0.1	0.1

Table IV. Overall understanding of crack propagation with different amendments

Amendment		CIF	Avg. % change compared to control
Vegetation	Crop species Non-Crop species	Increase Decrease	10-20 20-25
Fibre	Jute Coir	Decrease Decrease	30-45 30-60
Biochar	5%	Decrease	15-35
	10%	Decrease	40-60

5. Conclusion

The study provides a review of various sustainable amendments (fibers, biochar and vegetation) that have been utilized for remediation of soil from cracking. These amendments are useful as they are environment friendly and cost effective for Central Asian region for the application of green infrastructure and agriculture productivity. The review also provides insights into their mechanism of suppression of soil cracking by proposing a new factor (i.e., normalized CIF). Based on the proposed factor, the efficiency of biochar and fiber amendments are higher than that of vegetation. Vegetation may or may not have positive impact on cracking of soil depending on their shoot length. Whereas biochar and fibers generally have positive impact on reducing cracking. Among these amendments, wood biochar (10% content) and coir fiber (at 0.75 % content) seems to have highest efficiency in reducing cracking in soil. Further studies are needed to analyze the cost-effectiveness of soil amendments when applied on a large scale for soil remediation, especially in Central Asia. These studies should evaluate the application of materials across vast agricultural areas and green infrastructure. Additionally, they should assess the long-term economic benefits, such as plant growth, increased crop yields, and reduced degradation. Detailed analyses will ensure that soil improvement measures are economically viable and sustainable for widespread application in the region.

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