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Review Article

Soil Suction in Vegetated Soils: The Effects of Plant Roots and Evapotranspiration-A Review

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ISSN: 2637-8078

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Submission: March 24, 2025
Published: April 09, 2025

Volume 7 - Issue 2

How to cite this article: MV Shah*, MN Kubavat, PJ Mehta, RR Panchal, CR Chaudhary, et al. Soil Suction in Vegetated Soils: The Effects of Plant Roots and Evapotranspiration-A Review. Significances Bioeng Biosci. 7(2). SBB. 000658. 2025.
DOI: 10.31031/SBB.2025.07.000658

Abstract

Soil suction is the ability of soil to hold water against gravity and other external forces. It is a vital aspect of unsaturated soil mechanics, playing a key role in how soil holds water and maintains its strength and stability. This review describes the significance of soil suction, its measurement techniques such as the filter paper method and the combined effects of vegetation, plant roots and microbial processes on suction. Vegetation actively enhances or reduces soil suction via root water uptake and evapotranspiration, having an overall effect on slope stability, strength of soil and hydrological activity. This review synthesizes existing research about the effect of vegetation, roots and evapotranspiration driven soil suction while underscoring major causes and mechanisms. Various experimental and field studies analyze how different species of plants and root systems influence the process of soil-water interactions. It highlights the necessity of interdisciplinary research to develop sustainable, nature-based strategies for enhancing soil functionality and resilience.

Keywords: Soil suction; Unsaturated soil mechanics; Matric suction; Microbes; Plant extraction methods

Abbreviations: ETr: Evapotranspiration; Tr: Transpiration

Introduction

General concept of suction was initially developed by soil physicist in the early 1900's. Soil suction is the capacity of soil to hold water by capillary and osmotic forces, being of considerable importance in unsaturated soil mechanics, geotechnical engineering and agriculture. Soil suction comprises matric suction, which is due to capillary action in pores of the soil and osmotic suction, which is affected by dissolved salts. Parameters influencing soil suction are soil type, moisture, evapotranspiration, compaction, salinity, temperature and depth. Increased suction improves soil strength but decreases water availability to plants as well. Knowledge of soil suction is important in the stability of infrastructure, water management and sustainable land use. This review paper is divided into four distinct sections, the first of which covers the importance of soil suction, unsaturated soil mechanics and forest soils. The second section analyzes different methods for measuring soil suction with a focus on the filter paper technique. The third section studies the plant induced soil suction, the effects of plant roots, evapotranspiration and microbial activity on soil suction. The fourth section explores plant extracts, giving an overview of various plant extraction techniques.

Soil suction is very crucial to unsaturated soil mechanics-it affects perhaps the most essential soil properties such as conductivity, strength, compressibility and swelling potential-and would require a proper measure of suction in practice in the wide array of geotechnical applications, including pavement engineering, slope stability, foundation design and waste containment [1,2]. Total suction comprises matric suction due to capillarity in the soil and osmotic suction as a result of dissolved salts in the soil [3]. In natural, uncontaminated soils, the total suction is virtually equal to matric suction [1]. Moreover, various methods combining direct and indirect measures have been developed to measure soil suction, which includes insertion tensiometers, high-performance tensiometers, pressure-plate apparatus and thermal conduction sensors. Understanding and quantifying soil suction precisely will guide the design of stable and sustainable infrastructure whenever the associated soil is unsaturated.

Unsaturated soil mechanics

Research papers presented at the First International Conference on Soil Mechanics and Foundation Engineering in 1936, showed that there was a keen interest in the behaviour of soils both below and above the water table (i.e., saturated and unsaturated soils). An unsaturated soil has four phases: solids, air, water, air-water interface (contractile skin) and the pore-water pressure is negative relative to pore-air pressure. The contractile skin acts like a thin membrane interwoven throughout the voids of the soil, forming a fixed partition between the air and water phases [4]. As shown in Figure 1, the unsaturated soil profile consists of distinct zones.

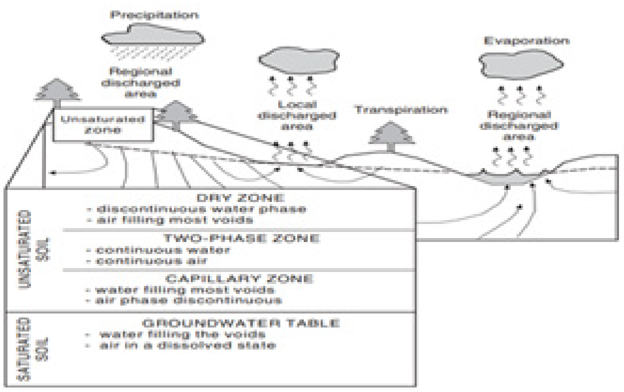

Figure 1: Subdivisions of unsaturated soil zone (vadose zone) on local and regional basis [4].

Forest soil

Forest soils, in which the forest cover has affected the development of soils, tend to have deeply rooted vegetation, substantial 'litter layers' or O horizons, cycling of nutrients and organic matter, such as wood, and extensive groups of soil-living organisms [JR Boyle 2005]. Forest-covered soils are also found that previously were not under forest vegetation but now have, for instance, plantations growing on land previously not naturally covered with forest. These soils are likely to be going through processes which impart them 'forest soil-like' properties, i.e., litter layers by trees, woody organic residues by deep roots and their attendant soil microbe and fauna populations. Like other soils, forest soils have evolved and are evolving, from geologic parent materials in different topographic locations in interaction with climates and organisms.

Discussion

Soil Suction measurement

Measurements of suction can be divided into two main categories; namely, direct method for measuring matric suction and indirect method for measuring matric, osmotic and total suctions [5]. Currently, a great amount of work has been done by researchers and geotechnical engineers towards the assessment of soil suction. Matric suction can be obtained through direct measurement of the negative pore-water pressure. Air pressure is considered to be pore-water plus pore-air pressure, while matric suction is the difference of air pressure and pore-water pressure. Measurement of water phase matric suction is accomplished through water and air phase separation using a ceramic cup or disk. There are many methods of applying both direct and indirect measuring techniques to determine soil suction.

Direct measurement techniques: Principle of operation of the Axis-translation method-instead of allowing the pore-water pressure to go negative and artificially high using atmospheric pressure applied to a soil sample, this method actually keeps pore-water pressures referenced to positive hence in the water compartment, it is kept as close to zero as possible- null-type axis-translation technique [6]. The method was adapted to measure the curves of other adsorption (wetting and drying) unconfined processes at low tension (less than 1500kPa). While a tensiometer is commonly used, a suction probe is an attachment for a direct measure of negative pore-water pressure of soil. Matric Suction Ridley and Burland (1993) have presented a suction probe for measuring soil matric suction. A mini suction probe, developed by Meilani et al. (2002), measures matric suction along the height of the specimen during an unsaturated soil triaxial test.

Indirect matric suction measurement technique: The indirect measurement of matric suction is usually done by employing a porous sensor constructed of certain materials, including filter paper, fiberglass, gypsum, nylon, sintered glass, clay ceramics, etc., and that conducts water away through the porous matrix. The water content of the sensor behaves as a measure of matric suction in the soil. Time Domain Reflectometry (TDR) was initially proposed to quantify soils' volumetric water content, which was later modified by Yu and Drnevich (2004) to evaluate gravimetric water content without subjecting the soil separately to tests for specific gravity and dry density. Basic electrical conductivity sensors are available commercially, and it is feasible to relate the electrical resistance of the porous block to matric suction. Thermal conductivity soil suction sensors are gaining popularity because of their reliability over wide suction ranges and independence from soil salt content. The filter paper method has been developed and applied by soil scientists and agronomists and is now continuing into geotechnical engineering practice as a routine method for suction measurement.

Indirect total suction measurement: The techniques used in the indirect total suction measurements are psychrometer, relative humidity sensor, chilled mirror hygrometer technique and non-contact filter paper method. This indirect measurement of total suction requires determination of other parameters and then using it in the psychrometer, which is dew point; then using relative humidity and temperature in both the relative humidity sensor and the chilled-mirror hygrometer technique; and water content in the non-contact filter paper technique. Filter paper has a large spectrum of measurement in suction. In the case of the non-contact technique, a dry filter paper is hung above a specimen of soil in a sealed container to attain equilibrium between the filter paper wet soil specimen at a constant temperature. Noncontact filter paper has a comparison near a chilled-mirror hygrometer technique as assessed by [7].

Filter paper method for measuring soil suction

Filter paper technique is very widely employed for measuring soil suction, the first work done by soil scientists and later geotechnical engineers [8-10]. This method measures a wide range of soil suctions using non-contact and in-contact methods.

In-contact filter paper method: In this method, matric suction is determined through water transfer between filter paper and soil until equilibrium occurs, turning the amount of water collected in the filter paper into suction using a calibration curve [ASTM D5298] as shown in Figure 2 [11]. However, the method fails under high suction ranges as vapor transport becomes the major means of moisture movement and takes long response times (7-14 days). Only ash-less filter papers like Whatman 42 and Schleicher & Schuell No. 589-WH should be used for accuracy. Nevertheless, while the method has some disadvantages, it is simple, inexpensive and very reliable if appropriate protocols are observed. In the in-contact filter paper technique one filter paper is placed in the middle of the soil sample sandwiched between two protective filter papers as shown in Figure 3.

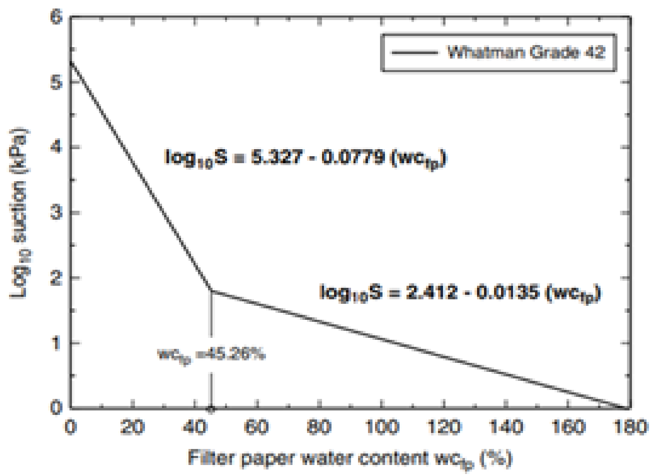

Figure 2: Calibration curve for Whatman grade 42 paper based on the wetting testing procedure (modified after ASTM D5298-10) [11].

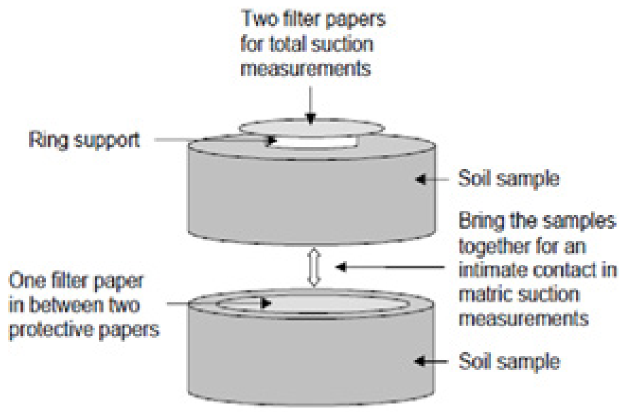

Figure 3: Total and matric suction measurements [13].

Non-contact filter paper method: In the non-contact method, as shown in Figure 3; two nos. of dry filter papers to be placed above a soil specimen in a sealed container, allowing only the exchange of water vapor that measures total suction. After the equilibrium, the water content of the filter paper is quickly determined and suction is calculated by using a calibration curve [8,10]. Its simplicity and low cost notwithstanding, the method has created doubts regarding its reliability, which is determined by the accuracy of the water-content versus suction calibration curve [12,13]. A calibration equation had to be specific to the filter paper used, with the most widely used being Whatman No. 42 and Schleicher & Schuell No. 589-WH (now called 989-WH in the USA). While ASTM D5298-94 governs both contact and non-contact methods (ASTM, 1997), contact methods become unreliable at high matric suction, and non-contact methods reduce in sensitivity at low total suction (Ridley & Wray 1996). Furthermore, long-equilibrium times and strict protocols are essential for accurate measurements.

Plant induced soil suction

Vegetation serves two main functions in terms of improving the slope stability. Mechanical contributions are primarily associated with roots intersecting a potential failure surface [Wu et al. 1979], whereas hydrological effects stem from both below-ground and Above-Ground Biomass (AGB). Vegetation, especially trees, increases soil suction significantly through mechanisms such as root-water uptake and energy interception, with the latter inducing greater suction levels for trees compared to grasses owing to their larger root systems. Also, vegetation is known to influence the soil-water retention characteristics associated with soil permeability [14,15]. Studies on the plant-induced suction have been conducted in the field on vegetated slopes through monitoring of matric suctions [Oorthuis et al. 2018; Smethurst et al. 2017; Springman et al. 2013], in laboratory conditions during drying [14], through drying-wetting processes [16], and performed probabilistic analyses based on field monitoring [17]. The main concern of most researchers is changes over time or space of matric suction concerning different conditions like compaction [18], illumination [14] and planting density [19], among others.

The work is, however, constrained by the laboratory-controlled conditions, which cannot capture the complexity of natural environments and thus have implications regarding its generalizations on real-world conditions. As shown in Figure 4, an overview of the three purpose-built boxes B, G and T in an atmosphere-controlled room illustrates the experimental setup used in such studies. Furthermore, Figure 5 presents a comparison of measured suction profiles between bare and vegetated test boxes before and after two weeks of monitoring, highlighting the influence of vegetation on soil suction [16]. According to Yildiz Root biomass, plant diversity and mycorrhizal fungi significantly enhance the shear strength and matric suction of root-permeated soils, indicating their vital role in slope stability [20]. However, limitations include the controlled laboratory conditions that may not fully replicate real-world scenarios, potentially affecting the generalizability of the findings to natural environments. Figure 6 presents the root-permeated specimens had lower water content than the fallow soil at the same matric suction.

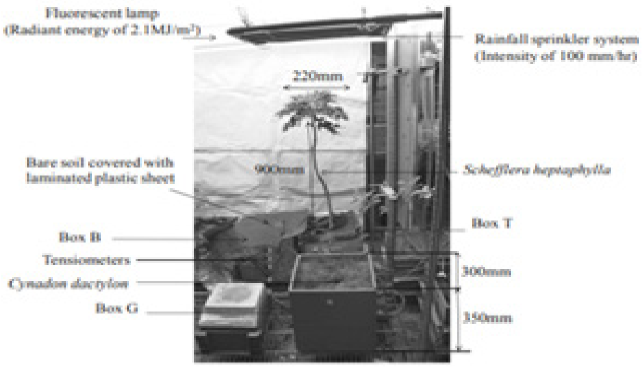

Figure 4: Overview of the three-purpose built-boxes B, G and T in an atmosphere-controlled room [16].

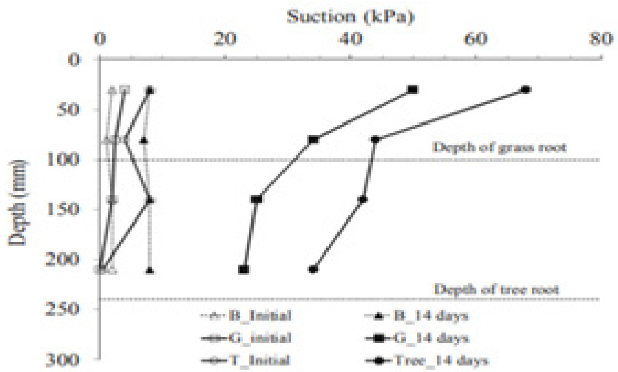

Figure 5: Comparisons of measured suction profiles between bare and vegetated test boxes before and after two weeks of the monitoring period [16].

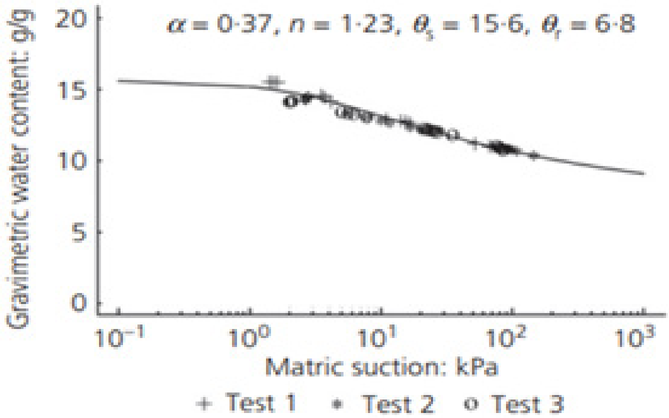

Figure 6: SWRC of the Praettigau soil and the fitting parameters for the equation of Van Genuchten (1980).

Soil suction influenced by tree roots

The changes in the Soil Water Retention Curve (SWRC) due to roots significantly influence soil suction, with vegetated soil exhibiting up to 100% greater suction compared to bare soil under dark conditions following a wetting event. The experiments had the tree species Schefflera heptaphylla conducted in a controlled setting at a temperature of 22.3 ± 1 °C and relative humidity of 53 ± 7%. But as a limitation of studies, data hinge on one tree species and controlled environment that are not clear representations of real-world happenings [21]. According to Garg et al. [22] the relationship between vegetation, soil water suction and slope stability has been investigated. Evapotranspiration (ET) is a soil water dynamic variable which increases soil suction and applies the influence to hydraulic conductivity and slope shear strength due to vegetation. Soil type: Silty sand (CDG). Plants studied: *Cynodon dactylon* (Bermuda grass) and *Schefflera heptaphylla* (ivy tree). Higher root zone suctions were observed for *Schefflera heptaphylla* than bare slopes and also those that had *Cynodon dactylon* during the dry periods. This can be attributed to the increased root biomass, higher evapotranspiration rates and possibly a stronger transpiration reduction mechanism of *Schefflera heptaphylla* [23] (Figure 7).

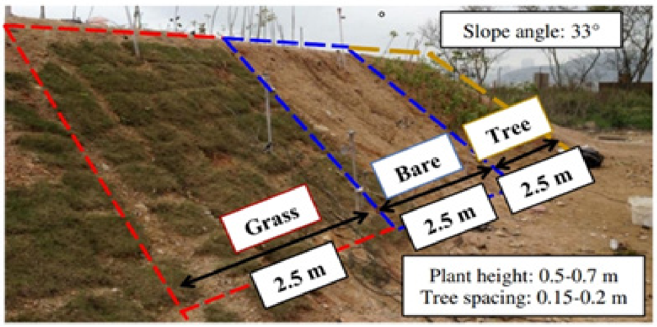

Figure 7: Slope with two different vegetation species (i.e. *Cynodon dactylon* (Grass) and *Schefflera heptaphylla* (tree)) and bare slope.

Evapotranspiration induced soil suction

Plant Evapotranspiration (ET) is identified as a hydrological process that caused soil suction, having a direct influence on the stability of geotechnical structures [21]. Evapotranspiration decreases soil moisture content through root water uptake, resulting in higher suction [22]. Garg et al. [23] examined the effect of Evapotranspiration (ETr) and Transpiration (Tr) on soil suction with the tree species *Schefflera heptaphylla* in silty sand. Their results showed that soil suction at certain depths grew with an increasing Leaf Area Index (LAI) because of increased radiant energy absorption and combined effects of evaporation from the soil. Consequently, ETr-induced suction was 3%-47% greater than Tr-induced suction, varying with LAI. Also, the research emphasized that increased Root Area Index (RAI) value was associated with higher soil suction since an increased root surface area improves water uptake efficiency [23].

Microorganisms in soil

The potential for biological properties of soil to influence passive and active treatment and management of organic chemicals in subsurface soil environment is widely acknowledged (Yong et al. 2007). As per the definition of Lipman (1931), the microorganisms included in the soil are bacteria, *Actinomycetes*, algae, *Protozoa, Nematodes, Rotifers* and insect larvae, which belong to the microscopic category invisible with naked-eye perception, except for some fungi and insects. These exist and utilize soil as a medium for their activities such as degrading organic matter, suppressing diseases and cycling nutrients (Jenkins 2005). Also, a soil gives sufficient nutrients and energy necessary for their growth and reproduction [24,25].

Role of soil microorganisms/microbes in soil suction

In addition to the roots, the biological system below ground consists of different micro- and macro-organisms constituting the soil biota (e.g. bacteria, fungi, algae, earthworms, insects), which are known to alter soil structure [26]. Among these, mycorrhizal fungi are crucial in enhancing the plant growth by increasing both the above- and below-ground biomass. They also change the soil structure by contributing to soil aggregate stability [27]. Therefore, it can be suggested that symbiosis between the host plant and the mycorrhizal fungi can improve the plant functions regulating the hydrological regime of the soil. Saffari R et al. [28] explored the influence of Microbial Induced Calcite Precipitation (MICP) on the retention properties of unsaturated fine-grained soils using filter paper experiments. The findings revealed that increasing bacterial concentrations (12% and 14% solutions) initially enhanced soil suction, with the water retention curves indicating significant changes in total suction as bacterial concentration varied. Specifically, the total suction required to drain the soil increased with bacterial concentration up to a point, after which it decreased due to competing processes like bio-clogging and bio cementation [28].

Plant extraction methods

Plant extraction is the separation of biologically active compounds from a plant such as a glycoside, alkaloid, phenol, terpenoid, or flavonoid these compounds have medicinal value. This is accomplished by the use of specific solvents for a particular technique so as to obtain the desired metabolite. The solvent extraction technique aims to remove the soluble metabolites of the plant from the plant cell that are not soluble. There are several broadly used methods for plant extraction that some plant types can provide such an efficient and low-cost way. Of all, phytonic processes have proved to be the most remarkable because of the numerous merits and multifunctional in comparison to traditional extraction methods. Figure 8 shows different plant extraction methods.

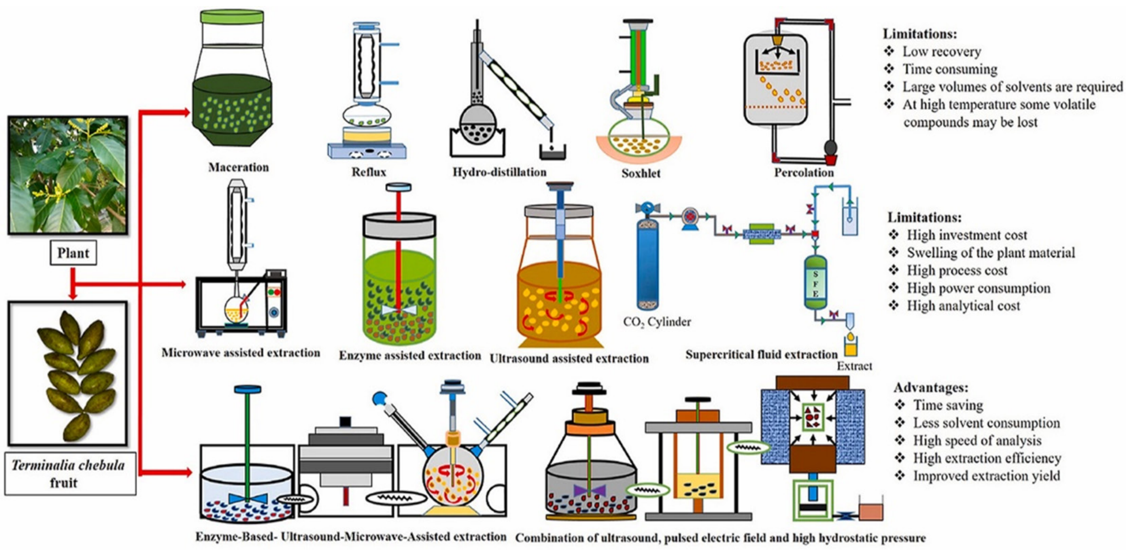

Figure 8: Various plant extraction methods.

Maceration, infusion, percolation and decoction: The bioactive compound extraction from plants is normally performed via the maceration method. It involves the soaking of course or powdered plant materials into methanol, acetone or water, which is kept in a sealed container for a minimum of three days at room temperature. During this period, the container must be stirred frequently and after it has settled, the mixture can be pressed, strained and filtered. Traditional extraction methods are usually dependent on the conduction and convection heat transfer, which makes the dependent solvent variable relative to the sought after compound. In addition to maceration, plant materials can also be infused or decocted with either hot or cold water. However, decoction is more suited for dense plant parts like barks and roots, where heat-stable, oil soluble compounds need to be extracted [29].

Soxhlet extraction method: In this method, a roughly powdered plant part is packed into the chamber of the Soxhlet apparatus, which is covered with a sturdy filter paper "thimble", and is placed into the apparatus. The flask placed on the heating mantle will fill with solvent vapor and pour it into the condenser. The cooled solvent will condense and pour into the thimble with plant materials and will make the extraction easy [30]. The process goes on as long as deposition of vapor from the siphon tube brings the solvent to the point which has no remaining solution. This process is the most effective one as it saves time, energy and the solvent while at the same time enabling large quantities of solvent to be used.

Accelerated solvent extraction (ase): Unlike maceration and Soxhlet extraction which are more tedious, Accelerated Solvent Extraction (ASE) is more rapid and efficient using considerably less solvent [31]. To avoid sample particles from adhering to one another and clogging the system, ASE employs the use of inert packing materials such as sand in stainless steel containers [31]. This technique facilitates extraction by manipulating the temperature and pressure of each sample. ASE, in particular, uses less than an hour to finish the extraction process [31]. This technique is much more rapid and controlled than conventional solvent extraction.

Microwave-assisted extraction (mae): According to Zhao et al. [32], this method utilizes microwave energy to enhance the movement of analytes from the sample matrix and into the solvent. Heat is generated at the interface of a material when microwave radiation comes in contact with the dipoles of the material which can be polar or polarizable, such as the solvent. Through conduction, this heat is then spread throughout the material. The application of microwave energy induces the rotation of dipoles resulting in the breaking of hydrogen bonds, further enhancing the motion of ionized solutes and increasing the dissolved solvent's penetration into the sample matrix [33].

Ultrasound extraction (sonication): Ultrasound-Assisted Extraction (UAE) is a recent advancement in technology that uses ultrasonic waves operating at a frequency of 20 to 2000 kHz to extract bioactive materials more efficiently. It effectively generates cavitation that leads to the destruction of the cell walls of plants, thus allowing better penetration of solvents and enhanced retrieval of desired compounds. As active ingredients are extracted at low temperatures, UAE not only saves time but also provides better stability for heat sensitive materials. This method is among the most popular in the pharmaceutical and food processing industries as well as in herbal extractions because of its effectiveness and low solvent requirement. On the other hand, using a high frequency ultrasound over 20kHz is detrimental for the integrity of bioactive molecules due to free radicals being produced.

Supercritical fluid extraction (sfe): SFE or Supercritical Fluid Extraction is an innovative method of extracting bioactive compounds from decent-quality plant materials using supercritical carbon dioxide (CO_2) fluid. Below 31.1 degrees Celsius and over the pressure of 7.38MPa, CO_2 occupies both liquid and gas state, which allows it to penetrate the targeted materials and dissolve the required compounds. Extracting the essential oils, plant flavors and other bioactive compounds is done with this method which is also very precise, environmentally safe and doesn't require any additional chemicals to perform its purification. This technique is very useful in the field of pharmaceuticals, food production and herbal medicine. Unfortunately, with all of its benefits, the high cost of SFE hinders its adoption in lower budget industries [30, 34-45].

Conclusion

A. Soil suction is essential in unsaturated soil mechanics because it forms a geotechnical stability, strength and water retention area. There are several indirect methods to measure soil suction, like tensiometers, pressure-plate apparatus and the filter paper method. However, none of these individual methods covers all ranges of suction.

B. The most common, simple, and economical method of assessing all ranges of total and matric suction values is the filter paper method. It does not require specialized equipment and operates under both field and laboratory conditions.

C. Much of the variation in suction in soil is caused by root uptake by vegetation and evapotranspiration, which means that different plants will give different suction values depending on their root system and transpiration quantities.

D. For deep-rooted plants, extraction of moisture resulting in increased suction and strength of soil occurs; for shallow-rooted plants, soil moisture will be retained. Besides density, it also has a very prominent role in water extraction; as density increases, water extraction and matric suction also increase, hence the stability of slopes is enhanced.

E. Microbial activities improve soil aggregation and suction characteristics, thus enhancing soil structure and stability by Microbially Induced Calcite Precipitation (MICP). Microbes alter pore connectivity of soil and shape biofilms that modify the water retention properties of soil in contact with them. Presence of mycorrhizal fungi also adds to soil cohesion as it improves root-soil interactions making soil less erodible.

F. Some ways to modify soil suction-controlling include plant extraction, with the techniques of maceration, Soxhlet extraction and supercritical fluid extraction strongly increasing retrieval efficiency of bioactive compounds. Bioactive compounds can be used to alter the soil's chemical profile affecting cation exchange capacity, permeability, and suction behaviour within the soil medium.

G. Natural biopolymers along with natural polymers have shown promise as an improved form of soil stability by binding soil particles and reducing desiccation cracks.

H. The need for additional cross-disciplinary studies brings together geotechnical engineering, microbiology and plant sciences to promote sustainable nature-based measures of soil stabilization.

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