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**REVIEW ARTICLE**

# A Study on the Combined Effects of Plant Root Growth and Evapotranspiration on Soil Suction Characteristics in Vegetation-Covered Soils

**M. V. Shah[1], M. N. Kubavat[1], P. J. Mehta[1], R. R. Panchal[2], C. R. Chaudhary[2] and N. M. Jadav[2]**
[1]Department of Applied Mechanics, L.D. College of Engineering, Opp. Gujarat University, Navrangpura, Ahmedabad – 380015, Gujarat, India.
[2]Department of Microbiology & Biotechnology, Gujarat University, Navrangpura, Ahmedabad – 380009, Gujarat, India.
***Corresponding Author:** M. V. Shah
**Email:** drmvshah@ldce.ac.in

**ABSTRACT**
*Soil suction indicates the inherent capacity of soils stored water against gravitational pull and all external forces-thus, it has a vital role in unsaturated soil mechanics. It controls the hydraulic behavior, strength, and entire stability of soil under partially saturated conditions. In this article are discussed the dynamic interactions between vegetation, plant roots, and microbial activity, as well as the influence of these biological factors on soil suction. Plants are known to alter water dynamics in soils with root water uptake and evapotranspiration, and this affects soil strength, slope stability, and water retention capacity. Various techniques for the measurement of suction such as filter paper are employed regularly for their determination and to study soil-water interaction. The review compiles and analyzes both experimental and field evidences about the influence of different plant species and root systems on suction behavior. It also describes the nascent role of microbial processes in changing soil structure and water regimes. Through meshing the perspectives of soil microbiology, plant sciences, and geotechnical engineering, this review makes a case for the need of an interdisciplinary approach toward the development of eco-friendly and resilient solutions for soil management and slope stabilization.*
**Keywords:** *Soil suction, Unsaturated soil mechanics, matric suction, microorganisms, plant extraction methods*

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## INTRODUCTION

The early twentieth century saw the first introduction of the concept of soil suction into various works by soil physicists. It speaks about the ability of the soil to hold and retain water via capillary and osmotic forces, vital for unsaturated soil mechanics, geotechnical applications, and agriculture. Soil suction can be classified in broad terms into two-thirds: matric suction-the suction associated with the capillary forces acting in the soil pores-and osmotic suction, resulting from the presence of dissolved salts in the water of the soil. The various factors influencing soil suction are soil texture, structure, moisture content, degree of compaction, solute concentration, temperature, ET, and depth of soil. Increased suction will reduce plant water availability while enhancing soil strength. Comprehending soil suction is an integral part of designing stable infrastructure systems and the efficient utilization of water resources for the attainment of sustainable land use practices. Soil suction is an essential variable in the mechanics of unsaturated soils and acts upon hydraulic conductivity, shear strength, compressibility, and swelling potential, which are characteristics with great significance in many engineering applications, including pavement construction and slope stability analysis, foundation engineering, and waste containment systems [1,2]. The total suction acting on a soil comprises matric suction, which is a result of capillary forces in the pore voids of a soil, and osmotic suction, which arises due to dissolved salts in the pore fluid [3]. In the majority of natural, uncontaminated soils, osmotic suction is often small and total suction can be considered nearly equal to the matric suction [1]. The different means of direct and indirect measurement developed for soil suction have enabled accurate determination of this parameter. These include standard tensiometers, advanced high-capacity tensiometers, pressure plate extractors, and thermal conductivity sensors. The knowledge pertaining to measuring and interpreting soil suction essentially advances the understanding of the behavior of soils under unsaturated conditions and serves the design of safe, durable, and sustainable infrastructural solutions.

**Unsaturated soil mechanics**

Researchers from around the world actually proved in the First International Conference on Soil Mechanics and Foundation Engineering that it was necessary to study how the soil behaves both above and below the water table, where soils are completely saturated. Unsaturated soils are much more complicated because they exist in four distinct phases: solid particles, water, air, and the air-water interface or contractile skin [4]. This contractile skin is a very thin yet continuous membrane running through the voids of the soil, acting as a stable boundary between the air and water phases in the soil. The pore-water pressure in such soils is generally negative as compared to the enclosing pore-air pressure. An unsaturated soil will show a profile consisting of the following distinct zones, each of which behaves uniquely with respect to water and mechanics, as illustrated in the figure below: Figure 1.

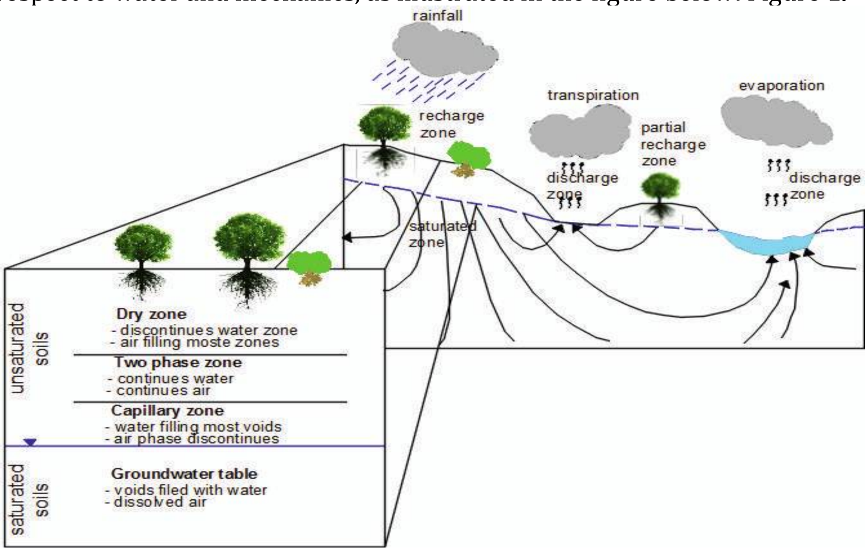



**Fig. 1 Subdivisions of unsaturated soil zone (vadose zone)[5]**

**Forest soil**

Climate, living organisms, and other soil-formation factors are partly responsible for the existence of forest soils. Forest vegetation profoundly influences soil formation and includes deep-rooted plant systems with well-developed organic surface layers (O horizons) and nutrient and organic matter recycling processes, including the decomposition of woody materials [J.R.Boyle, 2005]. They also support complex communities of soil organisms. Interestingly, properties resembling forest soils may develop on other lands even where no forest was previously located—such as those converted into plantations. Herein, processes formerly associated with a forest ecosystem, such as leaf litter accumulation, organic inputs from tree roots, and development of microbial and faunal communities, begin to cause changes in soil. The soil continues to age through interactions among climate, living organisms, topography, and geological parent material, just as it happens in other soil types.

**DISCUSSION**

**Measurement of suction characteristics of soil**

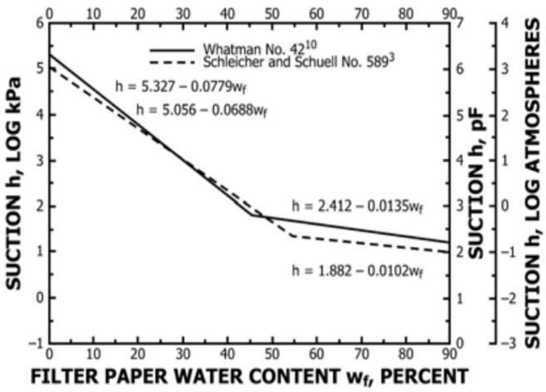
Suction measurements can be classified broadly into two categories; these are direct measurement of matric suction and indirect measurement of matric, osmotic, and total suctions [6]. On the one hand, direct methods primarily target matric suction, such as by taking measurements of the negative pore-water pressure using some instrument like a tensiometer or suction probe, or axis translation, which maintains positive water pressure for controlled studies [7]. TDR was originally introduced as a method for evaluating the volumetric water content of soils. In addition to this, Yu and Drnevich (2004) also modified their previous proposal of estimating gravimetric water content without the need for separate tests on specific gravity or dry density. Thus, the process is further simplified. More recently, a method for noncontact filter paper has been scrutinized for its accuracy and has yielded results comparable to those measured using the chilled-mirror hygrometer technique, as shown by [7]. In contrast, the indirect methods simply estimate matric, osmotic, or total suction through porous materials such as filter paper, fiberglass, or ceramics that reflect moisture conditions. Among these, the filter paper method is distinguished by its simplicity, low cost, and versatility. While this well-known method was initially adopted by soil scientists and agronomists, it is now widely accepted in geotechnical engineering as a reliable routine method to assess soil suction, especially that of unsaturated soils. The basic principle of the method consists of equilibrating filter paper with soil moisture and thereafter estimating suction from the moisture content of the paper. Its simplicity, minimal equipment requirement, and quite wide suction range make it particularly useful for laboratory as well as field studies.

**Filter paper method for measuring soil suction**

The filter paper method has become one of the most commonly used techniques for measuring soil suction, It was first invented by soil scientists and later appropriated by geotechnical engineers [8-10]. It is by far one of the better methods available to cover a great range of soil suction values and is applicable in both contact and non-contact modes.

**In-contact filter paper method**

In the filter paper technique, matric suction is measured by permitting the transfer of moisture between the soil and the filter paper until equilibrium is obtained. The water content of the filter paper is converted to suction values using the calibration curve discussed in [ASTM D5298] and shown in Figure 2 [11]. While the method is effective, it loses much of its reliability at high suction levels, where vapor-phase moisture transfer predominates. By this reason, equilibration times are grossly prolonged (in most instances 7–14 days). Only ash-free filter papers like Whatman No. 42 or Schleicher & Schuell No. 589-WH can be used in order to obtain reliable suction results. Although this may limit some procedures, the filter paper method remains a simple, inexpensive, and dependable procedure if carried out carefully. This method consists of placing a central filter paper between layers of soil and protecting both sides with other filter papers, as shown in Figure 3.




NOTE 1—Coefficient of determination r >0.99.

**Fig. 2 Calibration suction-water content curves for wetting of filter paper [ASTM**

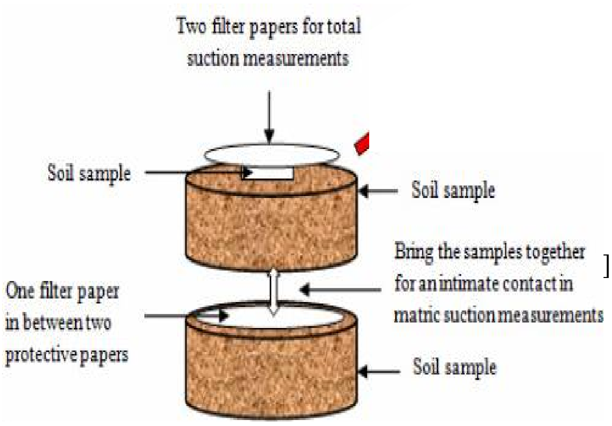



**Fig. 3 Total and matric suction measurements [12]**

The non-contact filter paper method is demonstrated in Figure 3. Two dry filter papers are placed above the soil sample in airtight containers. This arrangement allows only vapor-phase moisture exchange for measuring total suction and thus allows its derivation. After moisture equilibrium, the water content of the filter paper is determined with very rapid time, and suction is computed with reference to a calibration curve [8,10]. It is, however, well established that the measured suction improves with variations; indeed, this method is going to be shown to be quite simple and inexpensive because it brings much controversy into question concerning measuring suctions as such, which are indeed related to the accuracy of the water content–suction calibration curve [12,13]. The calibration must be specific to the filter paper type used, with the most widely used being Whatman No. 42 and Schleicher & Schuell No. 589-WH. The procedures for these contact and non-contact methods are presented in ASTM D5298-94 [14]. The contact method is less reliable at high matric suction while the noncontact method has been found to be less sensitive to small total suction [15]. Further, the principle of the method requires longer equilibration periods and compliance with certain protocols for the data to be accurate and consistent.

**Vegetative Influence on Soil Suction**

Vegetation increases slope stability through an important role involving mechanical support and hydrological function. On the mechanical side, roots strengthen and stabilize soils against failure by traversing potential slip surfaces [37]. With regard to hydrology, the aboveground parts of the plant and the roots influence the flow of water through and retention within the soil. Trees play a particularly significant role; they pull water from the soil through their roots and intercept rainfall with their canopies, which decreases soil suction. Generally speaking, the tree effect on soil suction would be stronger than that of grasses, mainly because trees have deeper and broader root systems. Water retention and permeability of the soils also influence the vegetation in slope stabilization over time [14,15]. Investigation concerning suction induced by plant roots has been executed using various field and laboratory approaches. Several studies have monitored changes in matric suction on vegetated slopes within field studies [34, 32], while laboratory experimental suction behavior was monitored during drying phases [14] through drying-wetting cycles [16]. Some have even incorporated probabilistic methods into analyzing data from field experiments [17]. The common matrix underlying the wide investigations would include evolution in matric suction with time and space depending on various factors, such as soil compaction [17], light exposure [14], plant density [19], among other factors." However, research has often restricted itself to such studies because they tend to be conducted under laboratory environments that cannot fully duplicate the complexity and variability of the real world: "The experimental setup as usually represented in Fig. 4 comprises specially designed test boxes labeled B, G, and T, put into a climate-controlled room." The actual experimental setting within which vegetation and soil conditions are simulated is shown in Figure 5: Comparison of soil suction profiles between bare and vegetated boxes before and after two weeks of monitoring. It is evident that these results show the impact of vegetation on soil suctions [16].

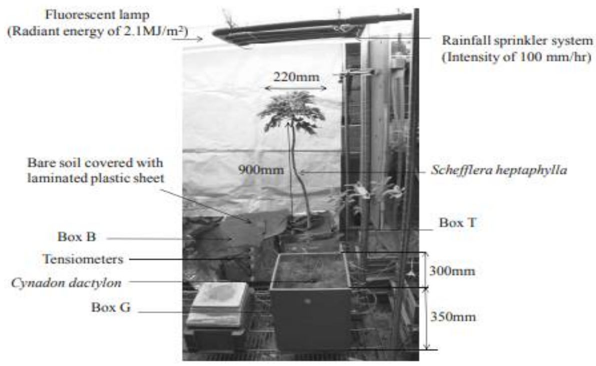



**Fig. 4 Overview of the three test boxes [16]**

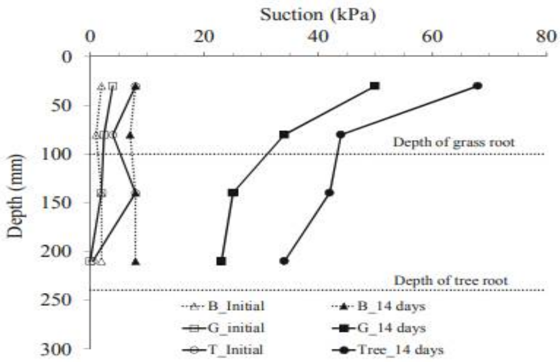



**Fig. 5 Comparisons of measured suction profiles between bare and vegetated test**

Yildiz states that root biomass, plant diversity, and mycorrhizal fungi directly affect the shear strength and matric suction of root-permeated soils and thus play a significant role in slope stability [20]. Limitations include laboratory-controlled conditions that may not adequately simulate real conditions, hence affecting how well the results can apply to natural environments.

**Soil suction influenced by tree roots**

It is evident that the saturation in a plant will very much affect the soil moisture retention curve (SMRC). The suctions level of the vegetated soils is made higher for the most part with more suctions in the vegetated soils than unplanted soils for nearly doubling that present in unplanted soils after soaking under moist conditions. Such trials were carried out with *Schefflera heptaphylla* within a controlled environment under the maintained temperatures of 22.3 ± 1 °C and relative humidity of 53 ± 7%. Such controlled experiments with single-species are the clear constraint because probably not all of such conditions will generate the responses that reflect the natural field conditions [21]. In their subsequent investigation, Garg et al. examined the interaction between vegetation, soil suction, and slope stability. The authors considered evapotranspiration (ET) as one of the crucial factors causing increase in soil suction, which in turn affects hydraulic conductivity and shear strength along slopes. For this purpose, silty sand (completely decomposed granite - CDG) was used as the test soil in conjunction with the two plant species: *Cynodon dactylon* (Bermuda grass) and *Schefflera heptaphylla* (ivy tree). The results indicated that *Schefflera heptaphylla* was able to develop higher root zone suction than in bare slopes or those covered with *Cynodon dactylon* during dry periods. This increased suction is likely due to higher root biomass, higher evapotranspiration rates, and possibly more effective mechanisms to close stomata or reduce transpiration under stress [22].

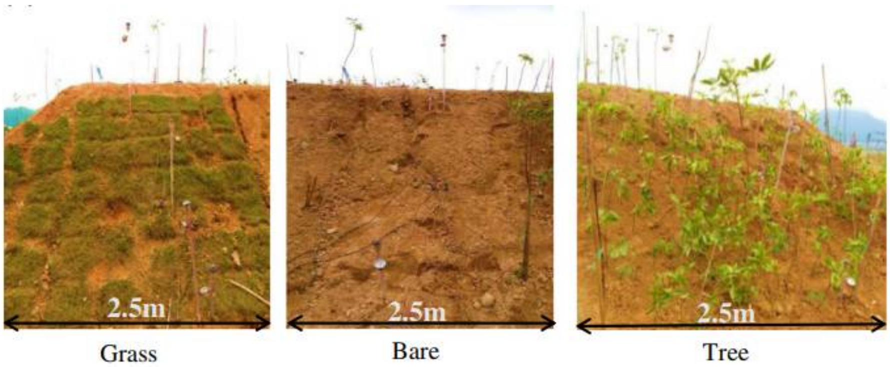



**Fig. 6 slope with two different vegetation species (i.e. *Cynodon dactylon* (Grass) and *Schefflera heptaphylla* (tree)) and bare slope**

**Soil suction induced by evapotranspiration**

Evapotranspiration (ET) is a significant hydrological process that generates soil suction and, consequently, influences the stability of geotechnical structures [21]. In other words, as plants absorb moisture from the soil through their roots, the ensuing drying of the soil leads to suction (Biddle, 1983). Garg et al. [23] further investigated the impact of evapotranspiration (ETr) and transpiration (Tr) on soil suction due to *Schefflera heptaphylla*, which grows in silty sand. Those suction readings at certain depths were found to increase with the leaf area index (LAI) enhancement due to higher solar energy absorption and evaporation from the soil surface. It also found that depending on LAI, the suction caused by ETr is 3% to 47% larger than that caused by Tr alone. According to the research, the larger root area index (RAI) causes higher soil suction, since the greater root surface area can extract increased amounts of water from the soil [23].

**Microorganisms in soil**

Remediation of soil for degrading organic contaminants in the subsurface environment is the well-studied contrast and interaction of biological components of the soil. Microorganisms of soil are defined as a diverse assemblage of minute or microscopic life forms, which include bacteria, actinomycetes, algae, protozoa, nematodes, rotifers, and insect larvae. Very few are visible with the naked eye, except perhaps for certain fungi or for the adult bodies the hydraurn of these agents in soil and certain ecological functions, such as decomposition of organic matter, cycling of nutrients, and suppression of plant disease. The soil also supplies a lot of nutrients and energy for these organisms' growth, survival, and reproduction [24,25].

**Role of soil microorganisms/ microbes in soil suction**

Underground ecosystems harbor many microorganisms and larger soil organisms (like bacteria, fungi, algae, earthworms, and insects) that together form the soil biota. They are known to majorly influence structures and pedogenic processes of the soil [26]. Perhaps the most important soil fungi are mycorrhizal fungi, as they have a vital role in improving plant growth and increasing root and shoot biomass. Additionally, they contribute to soil structure by stabilizing soil aggregates [27]. This partnership between plants and mycorrhizal fungi not only promotes plant health but also regulates water dynamics within the soil. R. Saffari et al. [28] studied how microbially induced calcite precipitation (MICP) can affect water retention behavior in unsaturated fine-grained soils based on the filter paper method. Their results indicated that higher concentrations of bacteria (12% and 14%) initially increased soil suction. Water retention curves further showed that there was a significant change in total suction with varying concentrations of bacteria first increasing and then decreasing due to the competing effects of bio-clogging and biocementation [28].

**Plant extraction methods**

Plant extraction means the extraction of bioactive materials like glycosides, alkaloids, phenols, terpenoids, and flavonoids from different plant sources. Such substances usually exert a very strong medicinal or therapeutic value. The specific solvents best suited for the extraction of particular bioactive compounds vary according to the methods of extraction employed. These methods aim at separating or removing bioactive constituents from the plant cell and leaving insoluble materials behind. The extraction methods commonly used include many that are cost-efficient and suitable for a particular plant type. Phytonic extraction techniques have recently become more popular because of their versatility and benefits over traditional methods. The different extraction methods for plant materials are profiled in Figure 7.

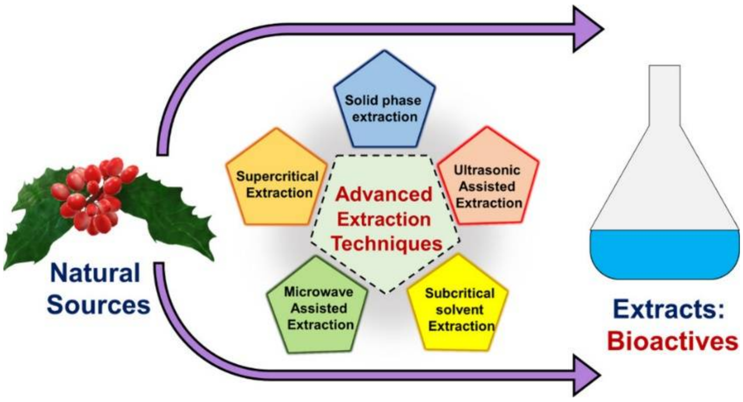



**Fig. 7 Different Extraction Methods for Plant Materials** [46]

**Maceration, infusion, percolation and decoction**

One of the most popular techniques for extracting bioactive compounds from plants is maceration. The coarse or powdered plant material is soaked in a solvent such as methanol, acetone, or water. It is kept in a sealed container at room temperature for at least three days, with stirring at regular intervals. At the end of the time, the mixture is allowed to settle and then pressed and strained before filtering to give the extract. Conventional extraction methods such as maceration mostly depend on conduction and convection for heat transfer, making solvent choice crucial depending on the target composition. Next to maceration, other methods of infusion and decoction are water-dominated methods. Decoction, especially, is preferred for hard plant parts, such as bark and roots, as it can extract heat-stable oil-soluble constituents [29].

**Soxhlet extraction method**

A Soxhlet extraction apparatus that was fitted with a filter paper thimble packed with coarsely ground material from plants. A solvent is heated in a flask with a heating mantle, then vaporized and brought up into the condenser, where it cools and drips down into the thimble containing the plant sample. In this manner, the solvent repeatedly pours over the material and penetrates it slowly. The siphon fills up at a certain point, and the solvent is returned back into the flask from which it came and the process continues. Its most efficient because it is able to perform extraction at different times with a relatively large volume of solvent, with less time and solvent being consumed [30].

**Accelerated solvent extraction (ASE)**

Accelerated Solvent Extraction (ASE) is faster and more efficient, consuming way less solvent compared to conventional methods of extraction such as maceration and Soxhlet extraction [31]. To avoid clumping of the sample particles and clogging of the system, inert materials like sand are used to pack the samples into stainless steel cells [31]. This method improves extraction by temperature and pressure modifications for optimized results. One key advantage of ASE is its speed, taking about an hour from start to finish, which makes it a quicker and much more controlled option than the conventional methods.

**Microwave-assisted extraction (MAE)**

The effect of microwave-assisted extraction involves the use of microwave energy to accelerate the extraction of the target compounds into the solvent from the plant material. Interaction of microwave radiation with polar or, sometimes, with polarizable products like certain solvents generates heat in these substances at molecular levels. This heat is then dissipated through conduction throughout the sample. The various energies facilitate the motion of dipole molecules, disrupting the hydrogen bonding and enhancing the mobility of ionized compounds, thereby allowing the solvent to penetrate through the plant matrix more efficiently [33].

**Ultrasound extraction (sonication)**
Ultrasound-Assisted Extraction (UAE) is a modern technique that employs ultrasonic waves, typically ranging from 20 to 2000 kHz, to improve the efficiency of extracting bioactive compounds from plant materials. The process works by creating cavitation bubbles that break open plant cell walls, making it easier for solvents to access and extract the target compounds. Because UAE operates at relatively low temperatures, it is especially suitable for preserving heat-sensitive components, while also saving time and reducing solvent usage. This makes it a preferred method in fields like pharmaceuticals, food processing, and herbal medicine. However, when ultrasonic frequencies exceed 20 kHz, the formation of free radicals can potentially damage the integrity of sensitive bioactive compounds.
**Supercritical fluid extraction (sfe)**
Through supercritical fluid extraction (SFE), forward-looking techniques are used to extract bioactive constituents from top-grade plant sources using carbon dioxide (CO2) as the extracting medium. Supercritical extraction of $CO_2$ occurs above 31.1°C and 7.38 MPa pressure, wherein the supercritical conditions send it to the state that has properties of both gas and liquid. Thus it penetrates the plant materials deeply and dissolves the compounds required. The main use of SFE is for extracting essential oils, flavors, and other active plant constituents at high precision with an ecological footprint and without hazardous chemical residues. It is also used in industries like pharmaceuticals, food processing, and herbal formulations. However, despite present advantages, the high operational costs are challenging and limit widespread use, especially in cost-sensitive segments [30, 34-46]

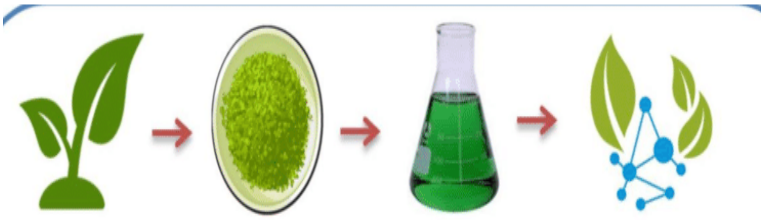



**Fig. 8: Extraction procedure of plant constituents**

**CONCLUSION**
The factors governing soil suction in unsaturated soil mechanics play a vital role as they affect stability and strength, apart from the ability of the soil to retain water. Although suction measurements may be made indirectly by using tensiometers, pressure plate apparatus, and the filter paper method, none completely encompass the entire suction range. The filter paper method is probably the best-known and most-widely applied costs and simplicity in estimating both total and matric suction. The method requires very little specialized equipment, making it suitable for both laboratory and field applications. Vegetation fundamentally influences soil suction through root water uptake and evapotranspiration. Suction values of water vary among different plant species, largely according to root depth and transpiration rate. An increase in suction is directly correlated to an increase in deep-rooted vegetation moisture extraction, which is directly related to an increase in soil strength. In contrast, a decrease in soil suction will occur through moist retention by shallow-rooted vegetation. The density of the soil also influences suction behavior. The higher the density of the soil, the better it becomes in terms of extracting water at higher matric suctions, thus more slope stability. Microbially induced calcite precipitation (MICP) is one way in which the microbial activity also affects the soil structure and suction properties. These microbes agglomerate the soils, modify pore connectivity, and form biofilms that affect the soil water retention characteristics. Mycorrhizal fungi further enhance the binding of roots to soil, thereby adding to the cohesion of the mixed soil and reducing erosion. The soil suction could be economically manipulated through plant extraction via Shells, Soxhlet, and Supercritical Solid Fluid Extraction. These plant-based processes can be useful in improving the extraction efficiency of bioactive compounds, which can be later used to alter the chemistry of the soil, hair cation exchange capacity, permeability, and diffident suction behavior. The stabilization potential of soil has been demonstrated with the application of natural biopolymers and other environmentally benign additives. These materials provide some level of bonding of soil particles and help reduce the formation of desiccation cracks. The interdisciplinary approach but with strong integrative framework focuses on solution based on geotechnical engineering, plant science, and microbiology through collaborative work will aid in formulating these nature-inspired

solutions against various environmental and engineering challenges in their long-term sustainable applications.

***Abbreviations:*** *Evapotranspiration (ETr), Transpiration (Tr)*

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