Unsaturated soil behavior under the combined influence of water-absorbing polymer and vegetation

thesis

submitted in partial fulfilment of the requirements of the degree of

DOCTOR OF PHILOSOPHY

by

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Dedicated to my beloved family and teachers

CERTIFICATE

This is to certify that the thesis entitled **“Unsaturated soil behavior under the combined influence of water-absorbing polymer and vegetation”** submitted by Bharat Rattan to the Indian Institute of Technology Guwahati, for the award of the degree of Doctor of Philosophy (PhD) in Civil Engineering is a record of bonafide research work carried out by him under our supervision and guidance. The thesis work, in my opinion, has reached the requisite standard fulfilling the requirement for the degree of Doctor of Philosophy.

The results contained in this thesis have not been submitted in part or full to any other University or Institute for award of any degree or diploma.

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STATEMENT

I do hereby declare that the matter embodied in this thesis is the result of investigations carried out by me in the Department of Civil Engineering, Indian Institute of Technology Guwahati (IITG), Assam, India.

In keeping with the general practice of reporting scientific observations, due acknowledgements have been made wherever the work described is based on the findings of other investigators.

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Abstract

Due to global warming associated with climate change, water scarcity is one of the major challenges that affects the economic, social, and environmental aspects of various countries and its food security. These situations affect the soil's physical properties and water retention characteristics, in general. It is well known that water retention of unsaturated soil plays an important role in the bioengineered slope, urban green infrastructure, and water use efficiency of agricultural soil. The water retention behaviour of unsaturated soil was quantified by the soil-water characteristics curve (SWCC), which is the relationship between water content and soil suction. It is an important relationship that helps to optimize the irrigation scheduling which aids in the management of water resources and increased water use efficiency. It is understood that the water retention characteristics can be improved by the addition of innovative soil conditioners that has the capability to store more water and use it during dry spells.

The water-absorbing polymer (WAP) is one of the viable soil amendments capable of improving the water storage in soil pores and release it during water stress condition. For establishing its utility, it is important to thoroughly investigate its impact on soil properties and plant response. The main objective of this research is to systematically explore soil-WAP-vegetation-atmosphere interaction under drought or water stress condition. The WAP interaction with soil and external ionic materials (such as fertilizers) significantly affects their water-absorbing capacity and overall performance. Therefore, the combined interaction of WAP- fertilizers and WAP degradation may inhibit the functionality of WAP, which needs to be thoroughly investigated by observing the changes in the SWCC of WAP amended soil. It is well-known that plant physiological parameters (stomatal conductance (SC) and photosynthetic yield (PY)) undergoes changes during the period of drought stress. However, there is lack of understanding on how these changes (SC and PY) can be linked with the unsaturated soil properties. Therefore, this study investigated the drought stress stages by establishing the relationship between plant's physiological characteristics and soil suction (SS). Furthermore, the short-term influence of WAP on the soil microbiota has been explored in this study. The performance of WAP and reduction in water retention capacity of WAP-amended soil was investigated for 12 alternate drying-wetting SWCC cycles. The result indicates the potential of WAP as an efficient soil conditioner even in the presence of fertilizer for countering the negative impacts of water stress conditions. The combined effects of WAP, plant presence, and drought had pronounced influence on the soil bacterial community. The study clearly demonstrated the usefulness of WAP-amended soil that has its utility in bioengineered slope, green infrastructure/urban green planning and arid region agricultural practices.

Keywords: water-absorbing polymer (WAP), WAP-soil-vegetation-atmosphere interaction, SWCC, fertilizer, stomatal conductance, photosynthetic yield, drying-wetting, degradation

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Abbreviation

WAP- Water absorbing polymer

WAC- Water absorbing capacity

USDA- United States Department of Agriculture

AS- Agricultural soil

BS- Brahmaputra silt

PS- Polyhouse soil

CW- Commercial water absorbing polymer

FW- Fly ash water absorbing polymer

XRD- X-Ray diffraction

EDX- Energy dispersive X-Ray

FESEM- Field emission scanning electron microscope

FTIR- Fourier transform infrared

SWCC- Soil water characteristic curve

SWC- Saturation water content

FC- Field capacity

PWP- Permanent wilting point

PAWC- Plant available water content

PWT- Permanent wilting time

SC- Stomatal conductance

PY- Photosynthetic yield

DIP- Drought initiation point

FDP- Final drought point

Chapter 1

Introduction

1.1) General

Ensuring food security and water availability under global warming related to climate change is one of the many challenges for current and future generation globally. For the same reason, sustainable development goals (SDGs) 1 (no poverty), 2 (zero hunger), 6 (clean water and sanitation), 12 (responsible consumption and production), 13 (climate action) enlisted by United Nations requires a special mention. It is understood that the knowledge of unsaturated soil plays a significant role in the water retention behaviour of agricultural soil (Jotisankasa and Sirirattanachat, 2017), efficient and optimal use of irrigation water (Mohamed and Paleologos, 2017), crop productivity in arid/ semi-arid regions (Adugna, 2016), bioengineered slope (Leung et al., 2017), and urban green infrastructure (Kumar et al., 2023). The behaviour of unsaturated soil is quantified by soil water characteristic curve (SWCC), which is the graphical representation of volumetric water content variation with soil suction (or negative pore water pressure) (Saha and Sreedeep, 2021). It is also named as soil water retention curve (SWRC). The knowledge of SWCC is central to the understanding of how easily the water is lost from the soil during drying. It is an essential input function for irrigation water requirement, irrigation scheduling, solute/ nutrient transport through the soil and predicting unsaturated hydraulic conductivity (Li et al., 2016; Leong, 2019). Additionally, SWCC was used in this thesis to understand the contribution of water absorbing polymer in enhancing the water retention/ storage within soil pores. Globally, drought has become a frequent natural disaster that has high socio-economic impact on countries and its food security. The frequent arid conditions and severe loss of moisture impacts the physico-chemical, hydrological and biological characteristics of soil (Tale and Ingole, 2015). In the event of water scarcity, conventional farming techniques are incapable to prevent the decline in crop productivity (Mishra et al., 2019). One of the possible ways to minimize the impact of water stress is the development of suitable soil amendment that ensures adequate storage of water during drought condition.

Water-absorbing polymer (WAP), also termed as Superabsorbent polymer (SAP), can absorb and retain large amount of water in a swollen state (Meshram et al., 2020). It was proposed in 1960s by the United States Department of Agriculture (USDA) as soil amendment. There are various hydrophilic groups (e.g., carboxyl groups, amino groups, hydroxyl groups, etc.) attached to the polymeric backbone, which can readily interact with water molecules (Li et al. 2004; Bao et al., 2011; Wu et al., 2012; Ahmed, 2015). The cross-linking makes the polymer insoluble in water and forms a gel, which can trap water within them (Maitra and Shukla 2014; Rivas et al. 2018). Due to their high WAC, these water-absorbing polymers are receiving much attention in various fields like the hygiene industry, food storage, wastewater treatment, tissue engineering, horticulture, green infrastructure, bioengineered slope, and agricultural practices (Zhang et al. 2014; Misiewicz et al. 2019). Recently, WAP has been extensively used for vegetation growth under water stress condition and heat waves (Meshram et al., 2020). The WAP can improve soil water holding capacity, increase water use efficiency, modify soil hydraulic conductivity/infiltration rates, and reduce surface runoff which in turn alter the SWCC (Abedi-Koupai et al., 2008; Bhardwaj et al., 2009; Saha et al., 2020a). The WAP helps to improve the water availability in the soil matrix and act as micro-water reservoirs in the soil pores, that can optimize irrigation in arid regions. Therefore, WAP can be considered as one of the possible solutions for management of water stress in plants during drought condition. It is important to quantify the effect of WAP on soil water retention and ensuring water availability for vegetation during drought condition.

The SWCC is an effective tool to quantify plant available water content in the root zone (Walczak et al., 2006; Gadi et al., 2019) by measuring the soil suction (ψ) and volumetric water content continuously under water stress condition (drying). The water stress can result in temporary or permanent damage to vegetation (Han et al., 2013; Saha et al., 2021b). Majority of the past studies related to water stress focused on either soil or vegetation characteristics (Anjum et al., 2017) by considering field capacity, permanent wilting point (PWP), stomatal conductance (SC), photosynthetic yield (PY), canopy area, leaf area index, root architecture (Tolk, 2003; Da Silva et al., 2014; Rolli et al., 2015; Gadi et al., 2017; Zhang et al., 2022). However, the combined interaction of soil and vegetation has not been explored in detail in the previous literature. Previous studies determined PWP from SWCC as the water content corresponding to a suction value of 1500 kPa, irrespective of plant species and soil texture (Garg et al., 2017; Zhang and Han, 2019). This reference value is often used for modelling water transfer in the soil-plant-atmosphere continuum in vegetation growth models (Richards and Fireman, 1943). The recent literature (Garg et al., 2020; Bordoloi et al., 2022) indicates that PWP at 1500 kPa may not be a correct procedure for defining plant water extraction and can lead to under-irrigation (early wilting) or over-irrigation (delayed wilting). Therefore, it is important to explore the uniqueness of wilting characteristics of plant considering both soil water status and plant physiology under drought condition.

It is well-known that fertilizers are an integral part of agricultural practices for meeting the essential nutrients required to improve vegetation growth and yield. It is hypothesized that the application of fertilizers may inhibit the performance of WAP due to its sensitivity to ionic solutions (Laftah et al., 2011). There are studies in the literature that investigated the effect of different fertilizers and the fertilizer amendment rate on the soil properties and vegetation growth indices without WAP amendment (Adugna, 2016). However, the impact of combined fertilizer and WAP influence on the water retention property of soil is unclear. The soil microbial community also plays a crucial role in vegetation growth and agricultural productivity. Therefore, the impact of WAP on the soil microbial community is an important consideration. Previous research has focused on studying the microbial communities in the context of water scarce environments (Fierer et al., 2003; Rolli et al., 2015). However, there is a lack of comprehensive understanding on the combined influence of soil amendment, vegetation, and water stress condition on the microbial community. Furthermore, the performance of WAP depends on the chemical properties of synthesized WAP as well as the physico-chemical properties of the soil. It is important to quantify the degradation kinetics of WAP performance to understand the frequency of soil amendment needed. There are no conclusive studies on the degradability, and long-term performance of WAP in the soil.

The main objective of this research is to systematically explore soil-WAP-vegetation-atmosphere interaction under drought or water stress condition. The performance of two different WAPs was quantified in the presence of organic and inorganic fertilizers for silt loam and silt. The progression of drought stress in plants was studied by relating soil suction and plant physiological indicators. The wilting characteristics of two plant species was quantified by linking soil suction with plant physiological parameters under field condition. The impact of WAP on soil water retention and plant yield under water deficit condition was studied for tomato species. The influence of WAP and vegetation on the taxonomic composition of the soil bacteria at the genus or species level was studied by performing 16S rRNA gene sequencing. The WAP degradation and subsequent reduction in the water retention capacity of the WAP-amended soil was studied by subjecting it to 12 alternate drying-wetting cycles. The results from this study have its impact on bioengineered slope, green infrastructure and arid region vegetation.

1.2) Motivation for this study

The necessity to efficiently utilize water for vegetation survival during water stress condition has motivated this study. It is established from the literature that water absorbing polymer (WAP) can absorb and retain a large quantity of water and helpful for vegetation growth. However, a thorough investigation is required to understand the effectiveness of WAP considering the interaction between soil, water, vegetation, fertilizers, and microbe. The efficacy and suitability of some of the sensors such as TEROS 21, 5TM, Leaf porometer, Mini-PAM-II for determination of WAP amended unsaturated soil behaviour and plant physiology under water stress condition need to be explored. This research attempts to fill the knowledge gap and provide valuable insights into the complex interactions between WAP, soil, fertilizer, vegetation, atmosphere, and microbial populations, that has an impact on green infrastructure/urban green planning and agricultural practices considering both vegetation growth and soil health under water stress condition.

1.3) Organisation of the thesis

The thesis is organized into eight chapters as follows:

Chapter 1 gives a general overview of the thesis, the motivation behind this research work, and its importance.

Chapter 2 reviews the literature comprehensively on the background research and identifies the gap areas. The objective and scope of the study are listed in this chapter.

Chapter 3 deals with the characterization of materials and the details of the adopted instruments in this study to meet the research objectives.

Chapter 4 describes the combined influence of fertilizers and WAP on the soil water characteristics curve (SWCC). Two different WAPs, two different soil textures and organic/ inorganic fertilizers were considered.

Chapter 5 unravelled the progression of drought stress in plants by relating soil suction and plant physiological indicators. The wilting characteristics was studied by linking soil suction with plant physiological parameters.

Chapter 6 presents the influence of WAP on the taxonomic composition of the unsaturated soil bacteria at the genus or species level using 16S rRNA gene sequencing.

Chapter 7 demonstrated the degradation of WAP by measuring the water holding capacity of WAP and soil-water characteristics curve (SWCC), subjected to 12 drying-wetting cycles.

Chapter 8 lists the conclusions and major contributions of this study. The limitations and future work of the study are also presented in the chapter.

Chapter 2

Literature review

2.1) General

There is a need to understand the water absorbing polymer (WAP)- Soil-Plant-Atmosphere interaction considering soil, plant and WAP characteristics. The present literature review explores important parameters, which are directly related to water stress conditions, details of studies related to WAP application in soil for green space/ infrastructure and agricultural practice. This include the details on WAP, unsaturated soil behaviour, plant parameters and atmospheric parameters.

2.2) Water-absorbing polymer (WAP)

The United States Department of Agriculture (USDA) developed a new material that can absorb significant amount of aqueous solution called superabsorbent polymer or water-absorbing polymer (WAP). The WAP contains a carboxyl group, amino group, hydroxyl group, and other hydrophilic groups that facilitate water absorption (Bai et al., 2014). Generally, WAP was synthesized using acrylic acid/ acrylamide and sodium/ potassium acrylate (Huttermann et al., 2009). The chemical structure of WAP in a swollen state are shown in **Figures 2.1 (A) and (B).** A detailed classification of WAP is shown in **Figure 2.1 (C).**

The synthesis of WAP depends on the required properties of WAP, such as water-absorbing capacity (WAC), swelling kinetics, re-swelling capability. This depends on various ingredients of WAP like monomer, initiator, backbone material, and crosslinking concentration (Bai et al., 2014). These factors influence the swelling behaviour and swelling rate of WAP. The WAP performance changes under varying internal conditions (such as composition, morphology) and external conditions due to the presence of different aqueous solutions and environment responses, represented in **Figure 2.1 (D)**. The environmental response such as temperature, light, magnetic field, and pH influence the behaviour of WAP (Schmaljohann, 2006). Synthetic WAP is commercially available in the form of particles, powder, and membranes. The WAP has wide range of applications in agriculture/ horticulture, developing personal hygiene products, food additives, environmental remediation, fire-retardant, tissue engineering (Venkatachalam and Kaliappa, 2023).

The WAC of WAP is sensitive to its physico-chemical properties, ionic concentration, and temperature of the external solution (Jensen, 2011). The effect of temperature on the WAC of two different WAPs including carboxymethylcellulose (RF) based WAP and isopropyl acrylamide (BF) based WAP is shown in **Figure 2.2 (a)**. The trend is completely different in the two WAPs due to the different compositions as well as the backbone material used for synthesis (Andry et al., 2009). The WAC decreases with increasing temperature from 15˚C to 35˚C in BF (WAP). In RF (WAP), WAC slightly increased up to around 50˚C due to higher degree of polymerization rate reported by Suo et al. (2007). In addition, the swelling rate decreased with increasing time and attained a constant value corresponding to equilibrium saturation condition (Nakamura et al., 2000).

The WAC of WAP was influenced by soil pH as shown in **Figure 2.2 (b)**. The WAC was maximum for neutral pH 7 and reduced towards acidic and alkaline pH. In an acidic medium, the H^+ ions replace the K^+ ions from partially neutralized potassium polyacrylate (WAP) leading to a neutral polyacrylate compound. On the other hand, the NaOH reacts with the polymer in an alkali medium. The Na^+ ions replace the K^+ ions to form a sodium polyacrylate compound that is anionic in nature. The rate of decrease in WAC in acidic medium is more than in basic medium. (Saha et al., 2021b). It is well known that WAP acts as a mini-reservoir in the soil pores absorbing water into the 3-D framework through osmotic pressure difference. The water flows out from WAP due to hydraulic gradient set due to drying of soil pores.

Prior research suggests that WAPs have effectively mitigated deep percolation and harmful impact on the vegetation growth during water stress conditions (Falatah et al., 1998). The WAP is considered to be one of the best management approaches for water management, improving fertilizer efficiency, and decreasing environment pollution (Abobatta, 2018). The WAP was found to influence water holding capacity, water use efficiency, hydraulic conductivity, and density that improves the water retention properties of the soil leading to enhanced vegetation growth under water stress conditions (Lejcus et al., 2018). In addition, WAP influenced the irrigation frequency, soil erosion, water run-off, soil microbial activity, and evaporation loss under well water conditions as well as water stress conditions (Al-Darby 1996; Orts et al., 2007; Abedi-Koupai et al., 2008; Bhardwaj et al., 2009; Lee et al., 2013; El-Tohamy et al., 2014). Recent studies reported that WAP has potential application in green infrastructure, bioengineered slope (Saha et al., 2020c). Still, it is not popular for the actual field application due to the

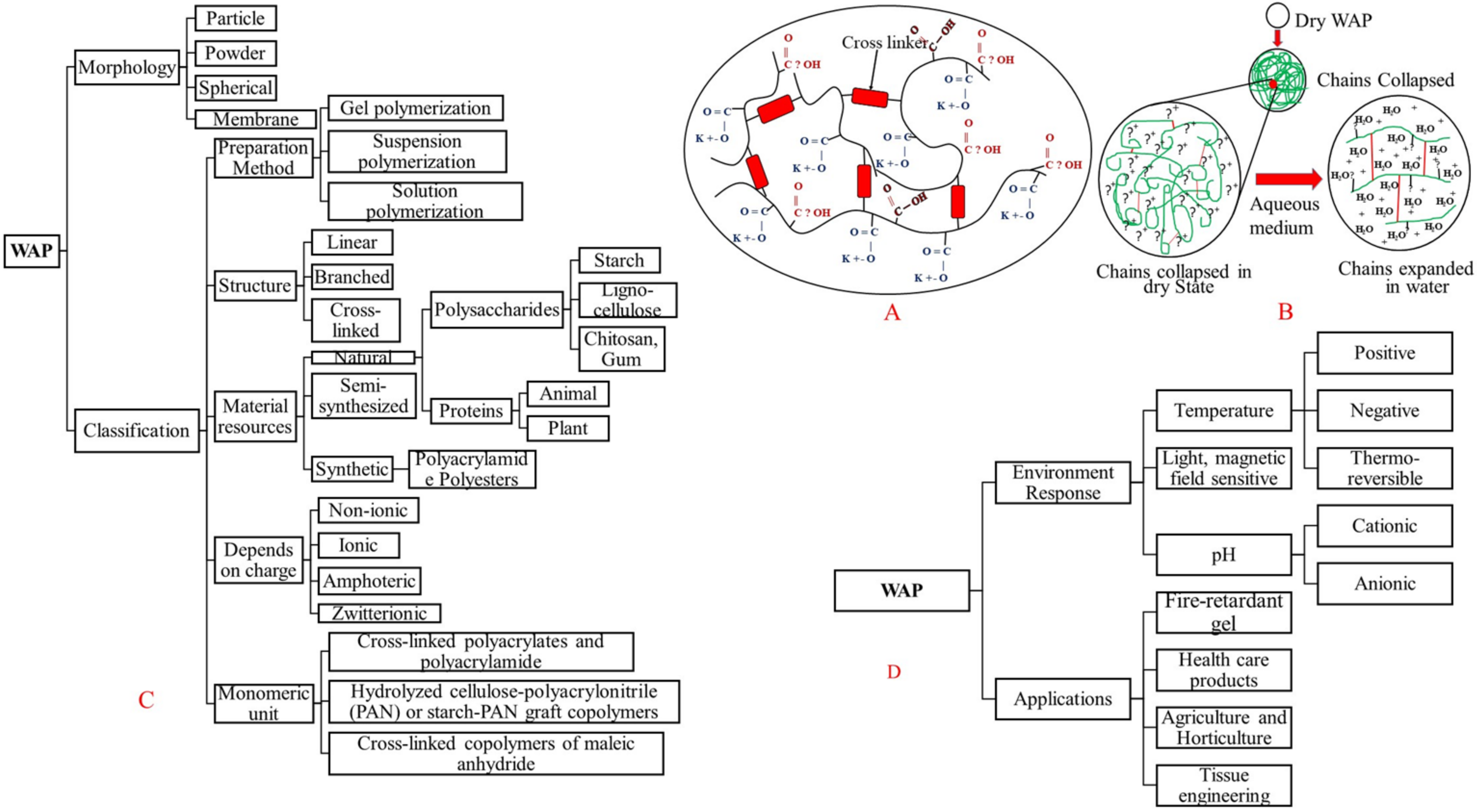


Figure 2.1: (A) Chemical structure and (B) Schematic diagram of acrylic acid-based WAP in swollen state (Huttermann et al., 2009, Zohuriaan-Mehr and Kabiri, 2008) (C) details of classification and morphology and (D) environment response and application of WAP

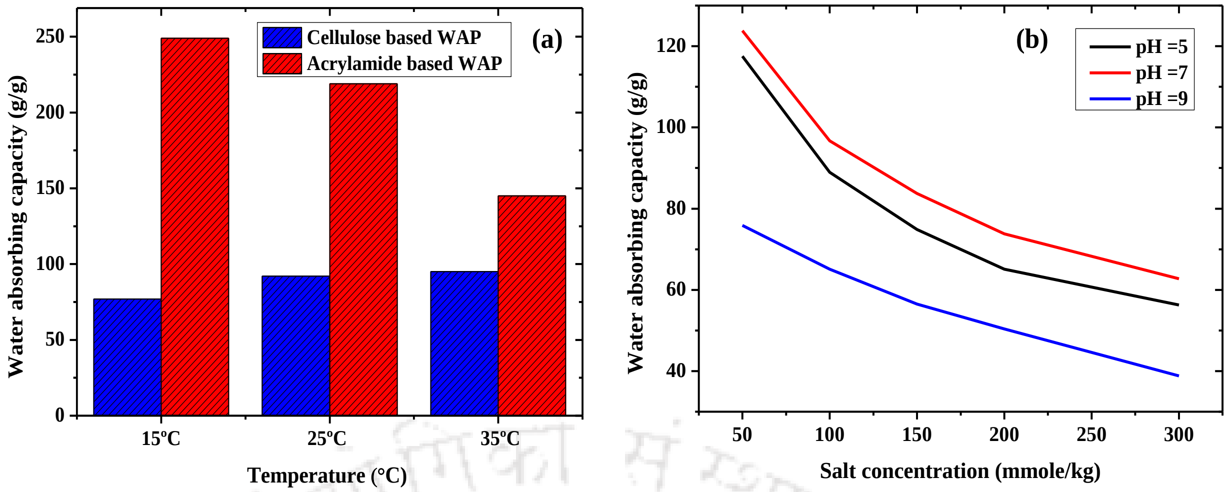


Figure 2.2: Effect of (a) temperature (Andry et al., 2009) and (b) pH (Saha et al., 2021) on water absorbing capacity of WAP.

limitations associated with high cost, poor salt resistance, and poor biodegradability. It is highly desirable to develop WAP that is economic and environment friendly by utilization of waste such as fly ash, biochar, and biomass.

2.3) Unsaturated soil mechanics

Soil plays a vital role in geotechnical engineering and urban green space/agricultural applications. There are various unsaturated soil characteristics such as soil-water characteristic curve (SWCC), soil density, hydraulic conductivity and soil microbial community that influence the vegetation growth. The following section aims to explore how the addition of WAP would influence these parameters.

2.3.1) Soil density

Soil density influences urban green space/ agriculture, SWCC, hydraulic conductivity, shear strength, vegetation growth, and impact on yield. The WAP performance was influenced by the soil density and depth of soil profile, which is termed as water absorbency under load. Lejcus et al. (2018) studies the effect of soil density on WAC with different depth of soil layers (10 cm, 20 cm, and 30 cm) shown in **Figure 2.3**. The WAC decreased with soil depth due to an increase in overburden pressure. An increase in soil density increased the time to reach equilibrium swelling (Rehim et al., 2004). The addition of WAP can reduce the bulk density of soil and reduction depends on the concentration of WAP amendment in the soil. (Bai et al., 2010; Neethu et al., 2018; Sarmah and Karak, 2020).

There is a need to further explore the role of soil density on WAP performance for various green infrastructure, bioengineered slope and agriculture.

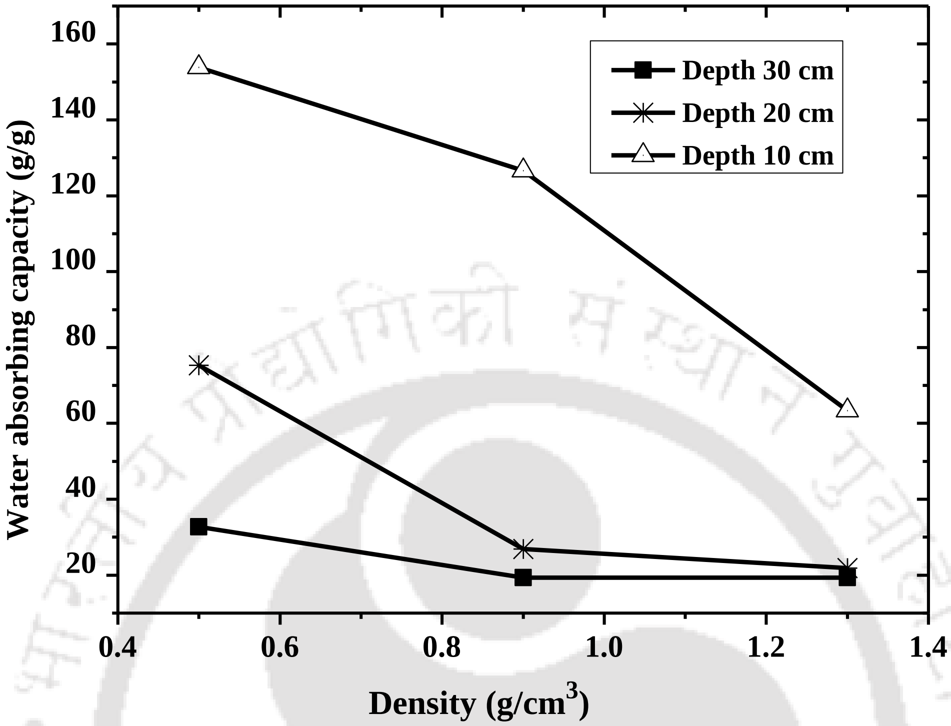


Figure 2.3: Effect of soil density on WAC at different depth (Lejcus et al. 2018).

2.3.2) Hydraulic conductivity

Hydraulic conductivity is crucial for determining the plant's available water content and irrigation scheduling (Wetzel and Chang, 1987). It was noted that bare soil shows higher hydraulic conductivity than vegetated soil due to the alteration in pore structure changes associated with the root system affecting water flow (Wallis and Horne, 1992; Buczko et al., 2007). Previous researchers have studied extensively to investigate the influence of WAP on the hydraulic conductivity of the soil. There is a lack of consistency in the literature on the effect of WAP on soil hydraulic conductivity. Some researchers have reported that the hydraulic conductivity reduces with the addition of WAP in the soil (Shahid et al., 2012; Narjary et al., 2012; Mohawesh and Durner, 2019; Xu et al., 2019; Song et al., 2020). WAP absorb and retain large amount of water leading to obstruction in soil pores thereby decreasing the flow. However, some literature reported that hydraulic conductivity increases with the addition of WAP (Bhardwaj et al., 2009; Zheng et al., 2015). As the WAP concentration increases, the soil loosens and allows water to move faster (Hussien et al., 2012). It is conclusive form the literature that hydraulic conductivity depends on WAP concentration in the soil (Zheng et al., 2020).

2.3.3) Soil-water characteristics curve (SWCC)

SWCC is a graphical relationship between soil suction (matric suction, negative water potential) and soil water content (gravimetric or volumetric water content, degree of saturation) (Lu et al., 2015). The various attributes of SWCC include AEV (air entry value), field capacity (FC), permanent wilting point (PWP), residual water content, water entry value and curve fitting parameters (Malaya and Sreedeep, 2012). AEV is the suction where the air first enters through the largest pore of soil (Brooks and corey, 1964). FC is the water content which is held after excess water drains off through vertical gravitational force (Cassel and Nielsen, 1986). PWP is the water content where the vegetation subjected to permanent wilt (Kirkham, 2014). Residual water content is the minimum water content below which there is no change in water content (Yang et al., 2004). Water-entry value is the suction at which water content increases (Birle et al., 2008). Feddes et al., (1982) reported 33 kPa as the field capacity and 1500 kPa as the permanent wilting point, in general, for all soil types and plant species. The conceptual representation of soil water characteristic curve (SWCC) is shown in figure 2.4.

The drying and wetting SWCCs are different (hysteresis) due to the alteration in soil structure associated with drying and wetting process. The knowledge of SWCC is mandatory for various soil-plant interaction projects like horticulture, agriculture and green space/ infrastructure where irrigation scheduling, water stress in plants, becomes important. In general, mathematical models are fitted to measured SWCC for quantifying unsaturated soil behaviour (Li et al., 2020). There are several empirical equations available in the literature for modeling SWCC (Pham and Sutman, 2023). The van Genuchten (1980) SWCC equation is widely used in the literature and various flow modelling software platforms, which falls under the category of sigmoidal curve.

Past literatures have discussed the influence of WAP addition on SWCC (Saha et al., 2020a). **Figure 2.5** represents the effect of a) different concentrations of WAP and b) grain size of WAP on SWCC. Increase in the concentration of WAP resulted in visible change in the SWCC due to the modifications of soil pore microstructure affecting the water retention capacity of the soil (Agaba et al., 2010). The empty voids are filled with the WAP, which increases volumetric water content in the soil (Bian et al., 2018; Rahmati

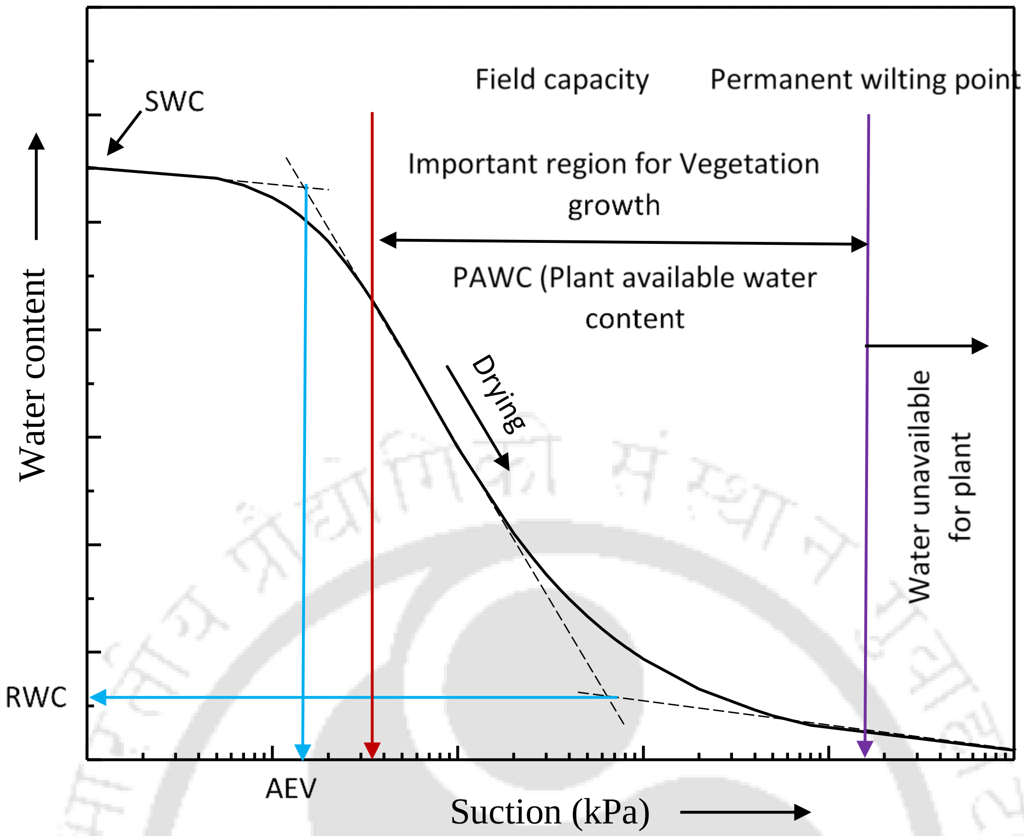


Figure 2.4: Conceptual representation of soil water characteristic curve (SWCC) (Saha, 2021)

Note: SWC: Saturated water content, RWC: Residual water content, AEV: Air entry value. The field capacity and permanent wilting point shown are only for representation. The actual numerical values will depend on the soil type.

et al., 2019; Saha et al., 2020a). **Figure 2.5 (b)** shows that WAP particle size influences SWCC. Small grain size of WAP may be more effective under water stress conditions (Bhardwaj et al., 2008).

Previous studies mainly focused on low suction range only (up to 100 kPa) due to the unavailability of suitable measuring sensor/ instruments for entire suction values. Due to the same reason, the studies focused mostly on sandy soil only (Sepaskhah and Shahabizad, 2010). Furthermore, the influence of WAP on permanent wilting characteristics, which may depend on both the soil type and plant species. Therefore, there is a need to understand a proper methodology for determining permanent wilting characteristics for different soil type, plant species and WAP amendment.

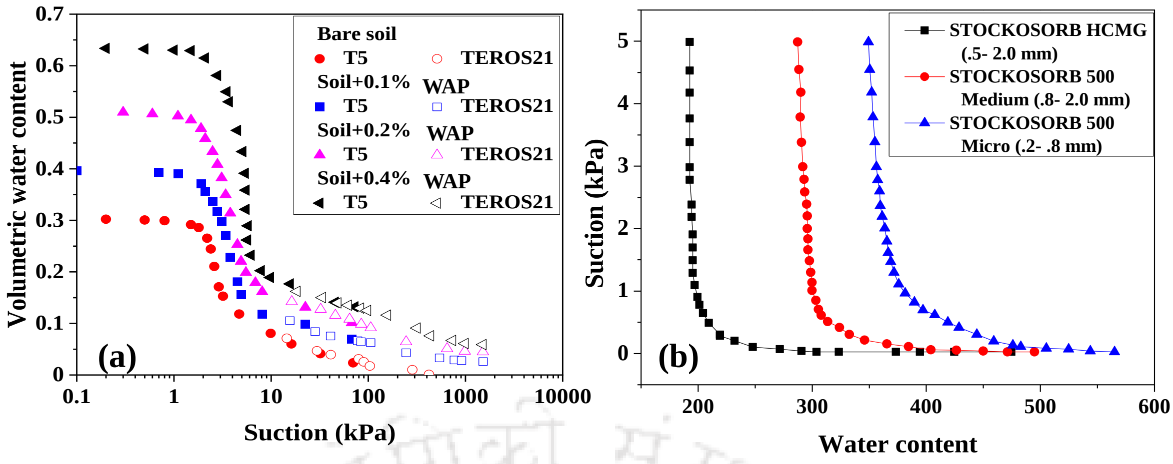


Figure 2.5: (a) Effect of various concentration of WAP on SWCC (Saha et al. 2020) and (b) effect of grain size of WAP (Bhardwaj et al., 2007)

2.3.4) Soil microbial community

Soil plays a crucial role in agriculture as it affects various aspects, including nutrient cycling, water availability, and plant oxygen, all of which are vital for plant growth and development (Swift et al., 1998). The microbial community, in particular, plays a vital role in maintaining soil health by supporting nutrient cycling, decomposing organic matter, and enhancing plant growth and productivity (Kibblewhite et al., 2008). Furthermore, it contributes to the development of healthy roots, which are crucial for plant well-being. Recent studies have focused on soil amendment for enhancing the vegetation growth. How the WAP application affect soil microbial community need to be understood in detail.

Previous research has mainly focused on studying microbial communities in the context of water scarce environment (Fierer et al., 2003; Rolli et al., 2015). Some studies have explored the individual impacts of WAP, plants, and drought (Dunfield and Germida, 2004; Li et al., 2014; Bogati and Walczak, 2022). However, there is a lack of comprehensive investigation into the combined influence of soil amendment, plant roots, and drought condition on the soil microbial community.

2.4) Plant parameters

Generally, plants require sufficient amount of water and nutrients during their life span. The plant growth and metabolic activities are affected due to the limited soil moisture availability. Insufficient water availability (water stress conditions) alters the morphological, physiological, biochemical processes and yield (Silva et al., 2013). Various parameters of plant responses under limited water availability are highlighted in **Figure**

2.6. The plant parameters are mainly distributed into shoot and root systems, which are discussed below in this section, which include leaf area index, stomatal conductance, photosynthetic yield, and root length density.

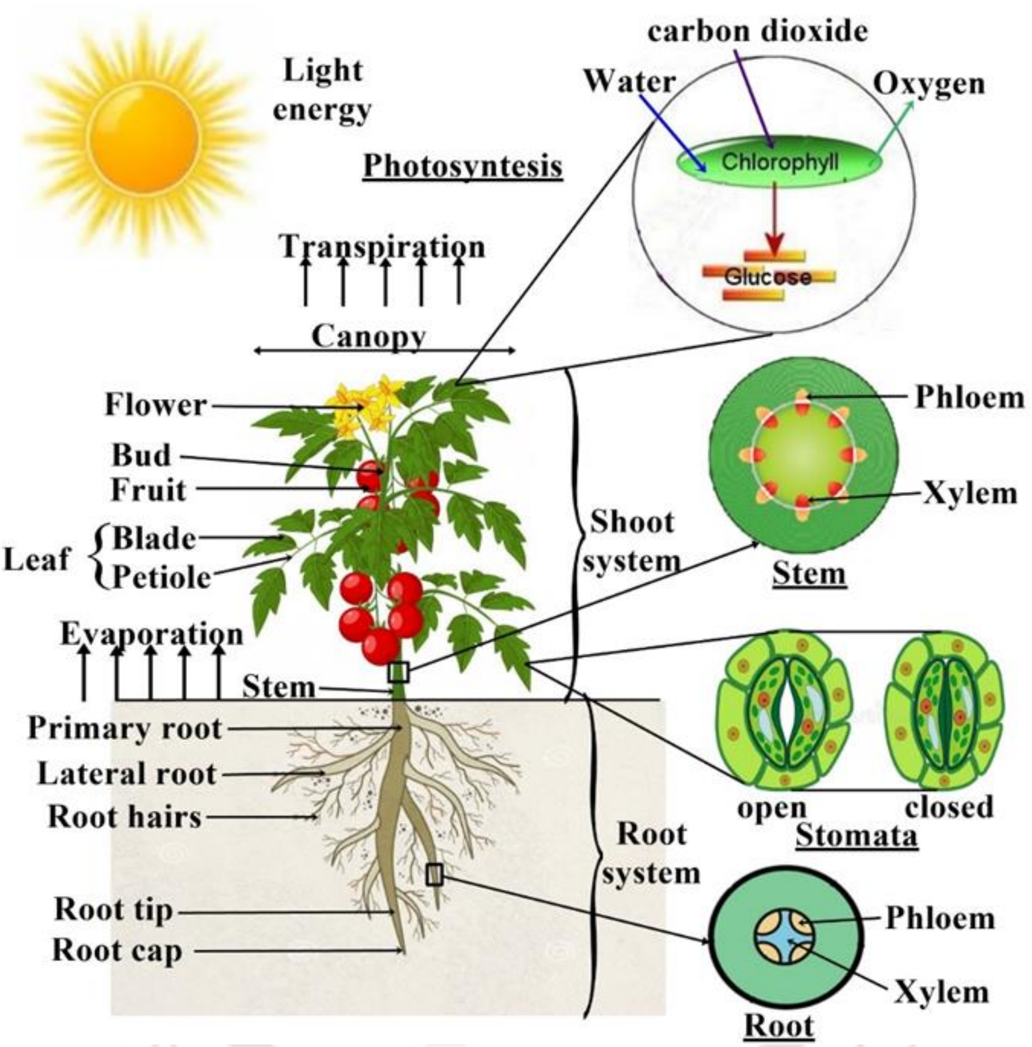


Figure 2.6: Details of the plant parameters affected by water stress condition.

2.4.1) Shoot parameters

2.4.1.1) Leaf area index (LAI)

Leaf area index (LAI) is defined as the ratio of one-sided green leaf area to the ground surface area and is a dimensionless quantity. Generally, LAI increases from zero to peak (maximum) and then reduces (Gitelson et al., 2003). During water stress condition, leaves compensate for water loss from its surface and try to maintain the LAI (Dehkordi, 2017; Anyia and Herzog, 2004). Water stress condition influences the rate of leaf expansion and leaf initiation, which influence the yield and plant development (Watts, 1974; Clough and Milthorpe, 1975). Yazdani et al., (2007) have reported that the LAI was influenced by WAP in soil, as shown in **Figure 2.7**. It was found that LAI has increased with the amendment of WAP and the maximum LAI was obtained for 225 kg ha^{-1} WAP concentration. The LAI was also influenced by unsaturated soil properties such as hydraulic conductivity, SWCC and bulk density (Scopel et al., 2004).

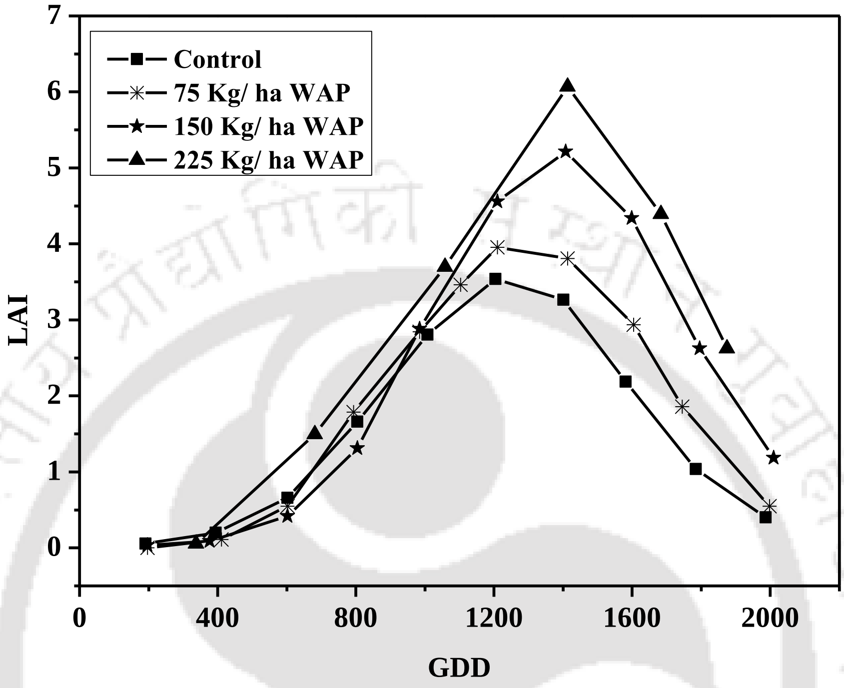


Figure 2.7: Effect of different WAP concentrations on leaf area index (Yazdani et al., 2007).

2.4.1.2) Stomatal conductance (SC)

Stomata are minute openings that are present on both sides of the leaf, facilitating gas exchange during photosynthesis between leaf and the atmosphere. The stomatal conductance (SC) plays an important role in water transmission between the plant and atmosphere, transpiration and removal of excess water. The SC can be measured by using the instruments such as a leaf porometer (types- steady-state, dynamic, viscous flow, and null balance). The SC range was found to vary from maximum to minimum value corresponding to soil suction variation from field capacity to the wilting point of the plant (Gadi et al., 2019; Garg et al., 2020). During water stress, abscisic acid alter the pH values and concentration of Ca^{2+}, Cl^{-} and K^{+}, which are present in the guard cell of plant (Wilkinson and Davies, 1997). These changes cause stomata closure resulting in SC reduction (Rodrigues et al., 2008). At minimum SC, stomata are completely damaged/

closed when soil suction corresponds to wilting point of the plant (Pei et al., 2000; Munemasa et al., 2015).

The SC was found to be influenced by various factors such as internal conditions: stomatal density, stomatal aperture, stomatal size, and external conditions: climate conditions, transpiration rate, and drought conditions (Medrano et al., 2002). The SC undergoes change during water stress condition, which influences plant's physical functioning and biological responses (Martin et al., 1999; Hetherington and Woodward, 2003). The earlier research demonstrated that the water deficit conditions are associated with decreases in SC (Bennett, 1987). The SC was found to be influenced by WAP because it alters the moisture status, suction, transpiration rate, etc. The effect of WAP on stomatal conductance (SC) under salinity and water stresses is shown in **Figure 2.8 (**Dehkordi, 2017). It was reported that SC was reduced under water stress conditions.

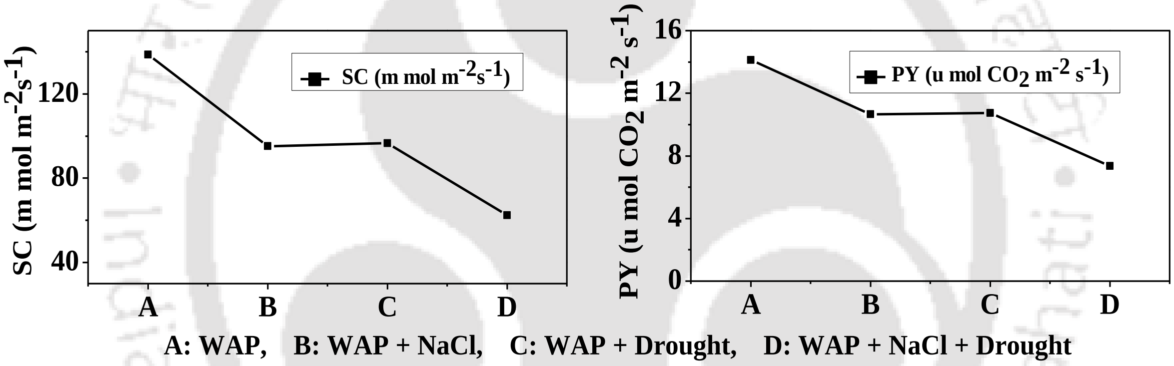


Figure 2.8: The effect of WAP on stomatal conductance (SC) and photosynthetic yield (PY) (Dehkordi, 2017).

2.4.1.3) Photosynthetic yield

The photosynthetic yield (PY) is derived from light intensity and the rate of photosynthesis. It is well known that PY is affected by water stress condition, which inhibits plant growth (Delfine et al., 2005). The WAP-amended soil has prolonged stomatal conductance, photosynthesis rate, moisture content, and provides sufficient CO_2 uptake by stomata, which helps mitigate water stress conditions (Yang et al., 2017). The effect of WAP on photosynthetic yield (PY) under salinity and water stresses is shown in **Figure 2.8.** Generally, PY can be measured by analysing chlorophyll fluorescence (Silva et al., 2013). The chlorophyll fluorescence is characterized by the F_v/ F_m ratio (F_v is the variable fluorescence, and F_m is the maximum fluorescence of the inductive curve) (Kitajima and

Butler, 1975). There are not many studies in the literature to explore the PY under water stress conditions, especially with the WAP-amended soil.

2.4.2) Root Parameters

The root system is one of the important plant parts for controlling the water movement and nutrients from soil to the plant (Ehdaie et al.,2012; Palta and Yang,2014; Wasaya et al., 2018). Coarse or tap roots establish root system architecture (RSA) that affects the water movement in the soil profile. The RSA is influenced by various factors such as soil temperature, moisture, soil suction, nutrients, and soil pH that influence plant growth and yield. The root system was influenced by water stress condition, which can alter the architecture and development of roots in terms of biomass, lifespan, root diameter, and root length density (RLD) (Kozlowski and Pallardy, 2002; Wasaya et al., 2018; Brunner et al., 2015).

2.4.2.1) Root length density (RLD)

Root length density (RLD) is pivotal in estimating the soil volume explored by a root system (Faye et al., 2019). The RLD is instrumental in regulating the cycling of water and nutrients for plant health. **Figure 2.9** compares RLD for water deficit and well-watered conditions. At a specific depth, root length density is higher in water deficit conditions than well-watered conditions, decreasing with the soil depth (Gyssels et al., 2002; Brook et al., 2008). There are not many studies in the literature considering the effect of WAP and aging on RLD.

2.4.3) Evapotranspiration

Evapotranspiration controls around 15% of the atmosphere's water vapor, which helps in maintaining water cycle (Wynne and Devitt, 2020). It is the main component of balancing energy and water for the application of green space/ infrastructure, geotechnical engineering and agricultural engineering (Takagi et al., 1998). Evapotranspiration determines soil moisture and plant water content, which affects both plant parameters and unsaturated soil behavior. Hu and Willson (2000) reported that evapotranspiration plays a most important role in explaining water stress variability. During water stress, the leaf tries to close the stomata, which reduces the transpiration rate and improves water use efficiency (Sands and Mulligan, 1990). A new drought index (SPEI- standardized precipitation evapotranspiration index) was introduced, which was based on precipitation and potential evapotranspiration (PET) (Vicente-serrano et al., 2009). The new index is useful for detecting, monitoring, and exploring the consequences of global warming and water stress on plants (Begueria et al., 2014).

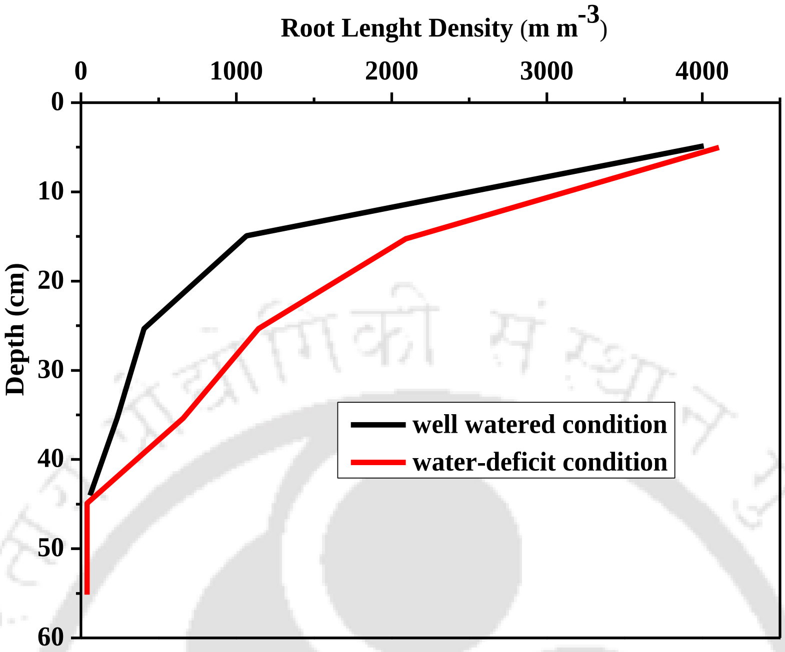


Figure 2.9: Comparison of root length density under well-watered and water deficit condition (Faye et al. 2019)

It was noted that the WAP has influenced evapotranspiration by reducing soil evaporation and plant transpiration, and increasing the available water content (AWC) (Daun, 2011, Saha et al., 2021a). **Figure 2.10 (a)** shows the effect of WAP on evapotranspiration in different soil types. Agaba et al., (2010) reported that average evapotranspiration was reduced with WAP amendment. Moreover, the effect of different WAP concentrations on the cumulative evaporation of loamy sand is shown in **Figure 2.10 (b)**. The results were obtained in the order: $T_{0.0} > T_{1.6} > T_{0.8} > T_{0.4}$. The reduction in evaporation with the presence of WAP may be attributed to the aggregation effect (Omran et al., 1987; Choudhary et al., 1995). The aggregation effect has influenced more at lower concentration of WAP that helps to reduces the evaporation rate. A higher rate of evaporation in higher concentrations of WAP was attributed to the higher water storage of WAP. Higher concentrations of WAP stored more water that could afford more evapotranspiration. However, more water is available for plant growth and yield (Al-Humaid and Moftah, 2007). There is a lack of understanding in the literature, the influence of WAP on the evapotranspiration rate during water stress condition.

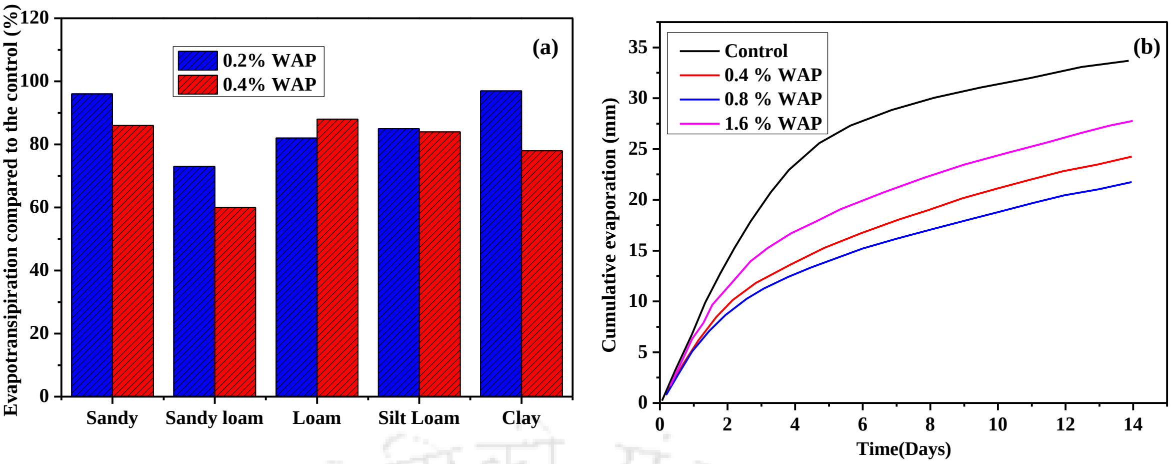


Figure 2.10: (a) Effect of WAP on evapotranspiration on different soil types (Agaba et al., 2010). (b) Effect of WAP on evaporation of loamy sand (Omran et al., 1987).

2.5) Salinity effect

Salinity accumulates soluble salts in the soil which adversely impacts plant growth and development due to osmotic inhibition (osmotic effect) of water availability, toxic effect of the ions and nutrient imbalance (Khan and Panda, 2008; Elfeky et al., 2007; Yan et al., 2015). Soil salinity is characterized by the presence of high amounts of ions such as Na$^+$, Mg^{+2}, Ca^{+2}, Cl$^-$ etc. These ions in excess are harmful to plant growth and unsaturated soil properties. Salinity affects physicochemical properties of soil including hydraulic parameters, water and nutrient uptake (Moghaddam et al., 2011). Salt influences soil microbial activity due to osmotic stress and toxic ions that plays an essential role in plant mineralization (Amato and Ladd, 1994; Yan et al., 2015). Salinity also influences photosynthesis, which reduces leaf area, chlorophyll concentration, and SC (Netondo et al., 2004).

The salinity has influenced the mechanical properties of WAP as well as changes in swelling behaviour. The WAP-salt solution interaction is classified as a) indissociable WAP (may weeken them) b) dissociated WAP (deswelling due to polyelectrolyte behaviour) (Huglin and Rego, 1991). The application of WAP reduced salt concentration in the leaves, roots and soil water solution because of its salt-holding capability (El Sayed 2011). According to Dehkordi (2017), the WAP modified soil had the lowest concentrations of salt ions such as K$^+$, Cl$^-$, and Na$^+$. Thus, the recovery of salt-affected soil is critical in promoting plant growth and development. **Figure 2.11** depicts a detailed flowchart showing the influence of salinity on the WAP-Soil-Plant interaction.

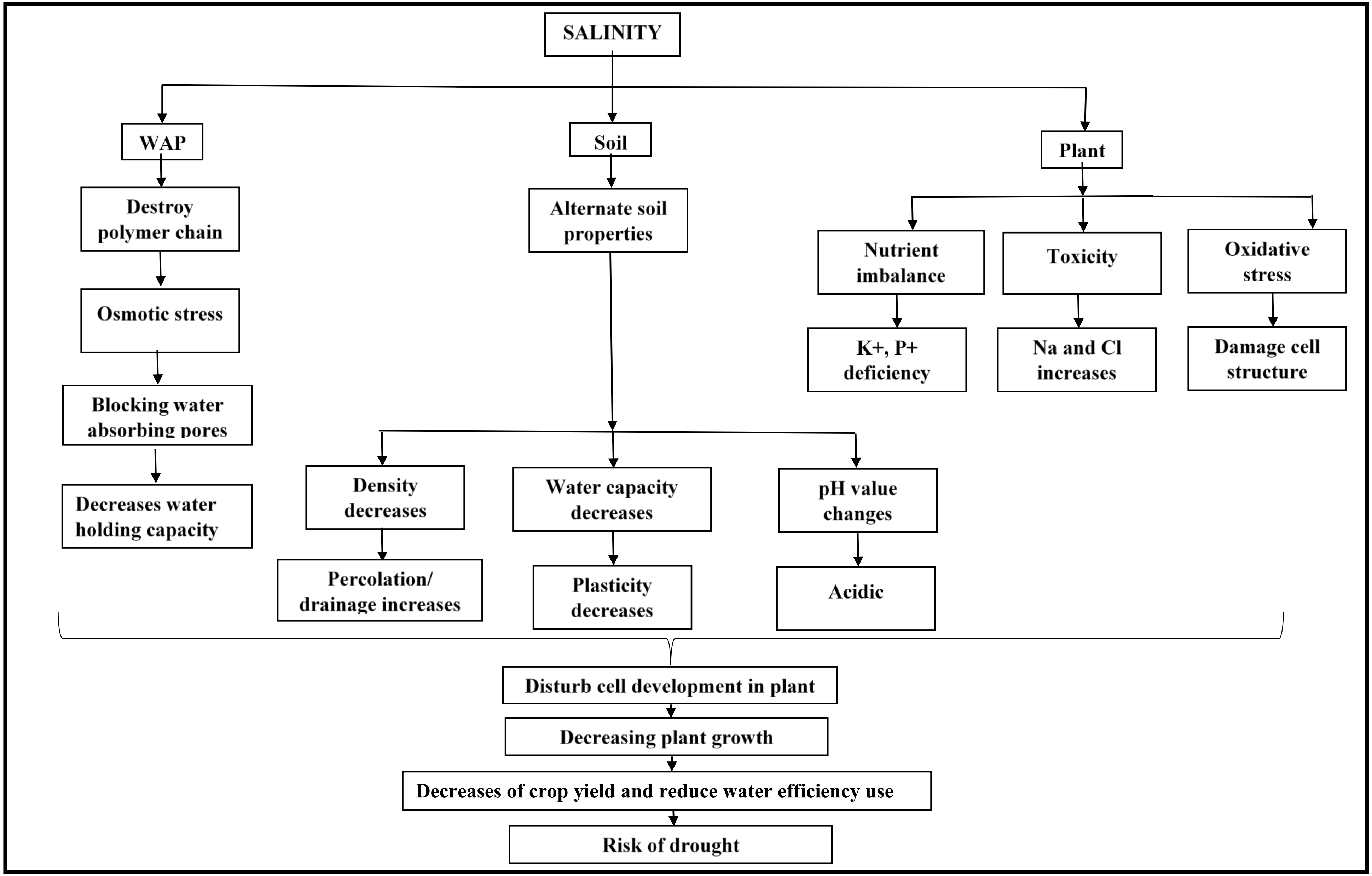


Figure 2.11: Effect of salinity on WAP-Soil-Plant parameters

Hamdy and Sfeir (2002) have investigated the utilization of WAP as a soil conditioner to mitigate the effect of irrigation water with varying salt concentration. The study observed that the utilization of WAP resulted in an enhancement of the plant's salt tolerance. Shi et al. (2010) have reported that the addition of WAP in saline soil can lower the salt concentration of the pore water by binding the salt ions to the large chain structure of the polymer. Nevertheless, the literature presents certain observations indicating that the inclusion of salt negatively impacts the water absorption capacity of WAP. Bowman and Evans (1991) and Zhang et al. (2014) have reported that the presence of salt cation has an adverse effect on the absorption capacity of WAP due to the formation of additional ionic crosslinks in the gel network. According to the findings of Saha et al. (2021), a notable decrease in the water-absorbing capacity was observed under saline or acidic conditions. The WAP exhibited higher sensitivity to multivalent ions than monovalent ions at equivalent molar concentrations due to the higher ionic strength of the latter.

2.6) Critical appraisal of the reviewed literature

The reviewed literature highlight the role of the knowledge of unsaturated soil in various application including urban green space/ green infrastructure, bioengineered slope protection with vegetation, and agriculture practices. Recent studies have highlighted the use of soil amendments like water absorbing polymer (WAP) that can alter the unsaturated soil properties. The WAP can absorb and retain a large amount of water or aqueous solution. It is used to improve the unsaturated soil properties, soil water holding capacity, plant available water, plant growth and reduces water stress during drying period. It acts as micro-water reservoirs in the soil pores, that becomes handy for optimizing irrigation in arid regions. A review of the existing literature has demonstrated that WAP can be used for water stress conditions to prolong the survival of plants and increase the water holding capacity of unsaturated soil. It was felt that the interaction of the WAP-soil-vegetation-atmosphere is not systematically studied in any of the literature. Such a type of study will help to understand the efficacy of WAP as a soil amendment for vegetation growth, yield, and irrigation scheduling. Hence, there is a need for an appropriate methodology to understand the behaviour of unsaturated soil amended with WAP and its impact on plant growth under water stress condition.

2.6.1) Research Gaps

- The effect of fertilizer on the performance of WAP in unsaturated soil under water stress condition is not explored.

- Most of the previous studies are limited to cohesionless soil (sandy soil) with the amendment of WAP.
- Influence of WAP on plant parameters including stomatal conductance, photosynthetic yield, transpiration rate, transpiration reduction factor (TRF) and yield are not understood in the previous research.
- Most of the WAP-soil interaction studies are restricted to laboratory scale only. More field evaluations are needed.
- The life span and application time of WAP are not studied in the previous literature.
- The effect of WAP on nitrogen fixation process in soil is not studied.
- Effect of WAP on soil salinity in the form of nutrients and other salts in the soil needs further investigation.
- Effect of WAP on soil microbial community need to be explored.
- Nutrient retention and soil erosion prevention in the vadose zone with the amendment of WAP requires a thorough investigation in view of bioengineered slope.

2.7) Objective and scope of the proposed work

The primary objective of the proposed research work is to investigate the unsaturated soil behavior under the combined influence of WAP and vegetation during water stress condition. The soil-WAP-vegetation-atmosphere interaction was quantified through laboratory and field measurements. Following are the scopes of the work for meeting the objective.

- To evaluate the combined effect of fertilizers and WAPs on the soil-water characteristics curve (SWCC).
- Laboratory and field evaluation of vegetation growth in unsaturated soil amended with WAP.
- To study the impact of water-absorbing polymer on the microbial community of unsaturated soil.
- To investigate the drying-wetting cycles on WAP performance in WAP amended unsaturated soil.

Chapter 3

Materials and Methodology

3.1) General

The materials used and experimental methodologies used in this research are presented in this chapter. It includes characterization of the basic physical properties of the soils and water absorbing polymer (WAP). Apart from this, details of the different generic instruments/ sensor used and their working principles are presented. This include instruments for measuring SWCC and plant parameters such as stomatal conductance and photosynthetic yield measured by leaf porometer and MINI-PAM-II, respectively.

3.2) Basic characterization of soils

3.2.1) General

Two soils for laboratory study and one soil for field study was selected for this research. Among these soil samples, agriculture soil was collected from Kamrup district in Assam, Brahmaputra silt was collected form the Brahmaputra river bank in Assam, field soil was collected from poly house at IIT Guwahati Campus in Assam, North-east India. The basic physical and geotechnical properties of these soils were determined using standard laboratory procedures following the guidelines stated in Indian standard code or ASTM standard. The source and designation of the soils are tabulated in **Table 3.1**.

Table 3.1 Details of the selected soil for this study

Serial no.	Soil material	Designation	Source
1	Agricultural field soil	AS	Saulkuchi, Kamrup district, Assam
2	Brahmaputra silt	BS	Brahmaputra river bank, Assam
3	Polyhouse soil	PS	IIT Guwahati campus, Assam

3.2.2) Physical characterization

The physical characterization of all the soils were performed and listed in **Table 3.2**. The soils were classified based on the physical characteristics.

Specific Gravity

The specific gravity was determined using the small density bottle or pycnometer (IS: 2727 (Part III/Sec 1) – 1980). Multiple trials were done for each material for obtaining consistent values of specific gravity listed in **Table 3.2.**

Hygroscopic water content

The hygroscopic water content of each soil material was determined by standard oven drying method (IS: 2720 (Part II) – 1973). Consistent result was obtained in each of the three trials performed and the average values were reported.

Grain size analysis

The sieve analysis and hydrometer analysis (ASTM D422-63 (2007); IS: 2720 (Part IV) – 1985) were performed to obtain grain size distribution curve. The grain size distribution curve of all the materials utilized in the study are presented in **Figure 3.1** and the details of percentage size fraction is listed in **Table 3.2**.

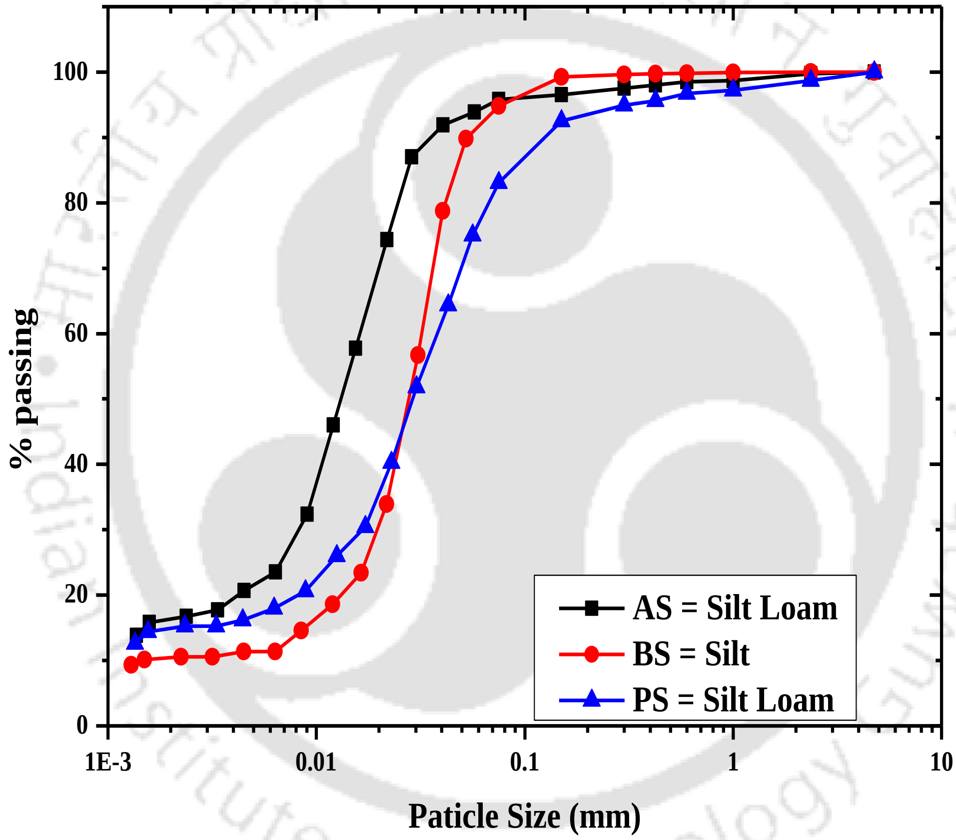


Figure 3.1 Particle size distribution curve of the selected soils.

Consistency limits

The consistency limits (i.e., liquid, plastic limit, and plasticity index) of the soil samples were evaluated in the laboratory by the Casagrande method (ASTM D4318 (2017b).

Electrical conductivity

The determination of electrical conductivity was carried out to obtain an indication of the content of water-soluble electrolytes in the soil samples (IS 14767: 2000).

Organic matter

The percentage of organic matter content of the soil samples was measured as per guidelines prescribed in the ASTM standard (ASTM D2974).

Classification

Depending upon the physical characteristics the classification of the soil samples was decided according to United States Department of Agriculture (USDA) provided in (USDA, NRCS 2010) and unified soil classification system (USCS) (ASTM D2487 (2017a)). The classification of soil is given in **Table 3.2**.

Table 3.2 Details of the physical properties and classifications of used soils

Physical properties		Soil Material		
		Agricultural Soil (AS)	Brahmaputra silt (BS)	Polyhouse soil (PS)
Source		Kamrup district, Assam, India	Brahmaputra river bank, near IIT Guwahati, Assam	Polyhouse, IIT Guwahati
Specific Gravity (G)		2.63	2.65	2.66
Hygroscopic water content (%)		4.2	3.7	4.0
Grain Size Distribution	Gravel (> 4.75mm)	0	0	0
	Sand (0.425- 4.75 mm)	4	5	17
	Silt (.002 mm - 0.75 mm)	79	84	68
	Clay (< 0.002mm)	17	9	15
Liquid limit (%)		37	32	39
Plastic limit (%)		21	20	23
Plasticity index (PI)		16	12	16
USCS classification		CL	CL	CL
Electrical conductivity (dS/m)		0.262	0.114	0.251
Organic matter (in %)		3.26	1.87	2.53
USDA classification		Silt loam	Silt	Silt loam

3.3) Characterization of WAP (CW and FW)

There are various kinds of WAP available in the market depending on their monomeric composition (homopolymer, copolymer) and backbone material (starch, cellulose, chitosan, attapulgite, montmorillonite). The physical and chemical properties of these WAP highly depended on their monomeric composition and presence of different hydrophilic groups. Therefore, characterization of the WAP is essential before using it as a soil amendment. A commercially available polymer namely Magic hydrogel, supplied by ACURO ORGANIC LIMITED, India were used in this study and designated as CW. It is an acrylic based polymer with acrylamide cross-linked in the polymeric structure. Hence, the primary hydrophilic group present in this WAP is carboxylate group and amine group. The fly ash based WAP (FW) was synthesized in-house by considering fly ash (FA) as backbone material, N, N′- methylene-bisacrylamide (MBA) as crosslinker, ammonium persulfate (APS) as initiator, and acrylic acid (AA) as monomer with partially neutralized with NaOH through graft polymerization. The detailed procedure of synthesis is reported in the literature (Saha et al., 2020d). FA-WAP is an already in-house synthesized WAP for mitigating drought stress in plants. However, previous studies have not tested its efficacy in the presence of vegetation, fertilizer in the soil, different plant species, and the influence of WAP on soil microbial community. For studying these research questions, FA-WAP was considered in this study along with a commercially available WAP (Com-WAP).

Partially crosslinked potassium-acrylate based WAP has been utilized for improving water retention behaviour in agricultural applications. Previous researchers have indicated that such WAPs are non-toxic and environmentally safe (Klein & Poverenov, 2020; Skrzypczak et al., 2020). The backbone material fly ash may contain different heavy metals depending upon the source of coal. Therefore, a toxicity characteristic leaching procedure (TCLP) was performed for the fly ash as well as the FA-WAP to understand the leachability of various heavy metals, including Pb, Cd, Cr, Ni, Cu, Zn. It was observed that the leachability of these heavy metals is well below the regulatory value, as proposed by the United States Environmental Protection Agency (USEPA 2002) and World Health Organization (WHO 1996).Performance of these WAP’s (CW and FW) were evaluated by measuring its water absorbing capacity (WAC), swelling, re-swelling capability and degradation in its performance.

3.3.1) Water absorbing capacity (WAC)

The water absorbing capacity (WAC) and the swelling characteristics of CW and FW were determined in three different types of solution including distilled water, tap water and a solution prepared by adding 0.9% NaCl to distilled water. The main purpose of using water from three different sources is to verify the influence of quality of water on the WAC. It is quite well known that WAP consists of different hydrophilic group by means of chemical cross-linking. Therefore, presence of any ions or impurity can affect WAC .

For the measurement of WAC, sufficient amount of water or salt solution was taken in a beaker and a specific amount of dry WAP was added in the beaker. The dry WAP particles were then allowed to absorb water at the ambient temperature till the swelling equilibrium of the particles have reached. Swollen samples were separated by filtering it through a filter paper for 30 minutes and drained under gravity. The adopted methodology for the measurement of WAC is shown in **Figure 3.2**. After draining out the excess water, the swollen sample was weighed to determine the amount of absorbed water and the WAC was then calculated with the following equation.

$$Q = (m_2 - m_1)/m_1 \qquad \text{Eq. 3.1}$$

where, Q is the WAC of the WAP; m_1 and m_2 are the weights of a dry sample and a water swollen sample, respectively. It can be noted that Q was calculated as gram of water per gram of dry WAP.

The obtained WAC of the WAP in distilled water, tap water and salt solution are presented in **Figure 3.3**. It can be seen that the amount of absorbed water drastically decreased from 458 g/g of CW in distilled water to 377g/g of CW in tap water whereas addition of 0.9% NaCl salt has decreased the absorbency of the CW to 76g/g of dry sample. Similarly, in FW, water absorbency decreased from 317 g/g in distilled water to 235 g/g in

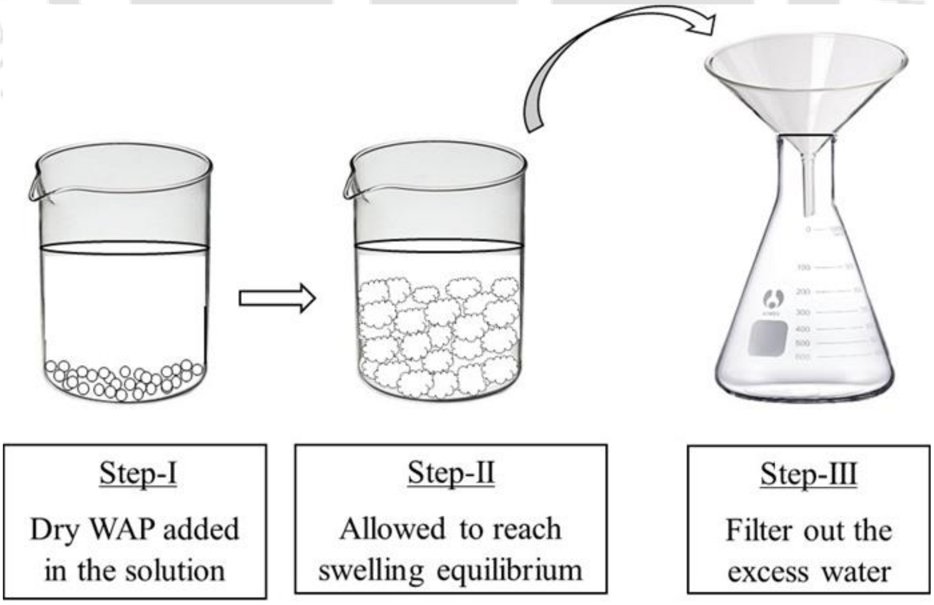


Figure 3.2 Methodology adopted for WAC determination

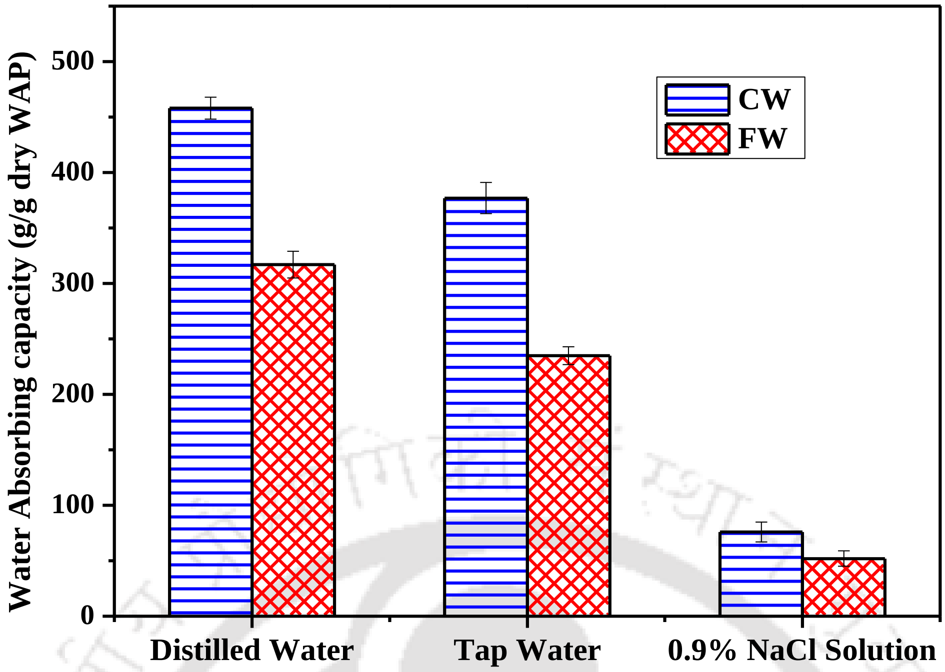


Figure 3.3 WAC of the CW and FW in distilled water, tap water and salt solution

tap water whereas addition of 0.9% NaCl salt has decreased the absorbency of the FW to 52 g/g of dry sample. The difference in absorbency in distilled water, tap water and salt solution can be attributed to the osmotic pressure differences between polymeric network and external solution, because of the salt ions in the solution (Feng et al., 2014; Zhang et al., 2014). Presence of salt ions can increase ionic strength of the solution which create anion-anion electrostatic repulsive force between the polymer network and external solution, thereby decreasing swelling (Li et al., 2014). Due to increasing the ionic strength, the osmotic pressure difference is decreasing resulting in less WAC (Zhang et al., 2015).

3.3.2) Swelling kinetics of WAP

In order to evaluate the swelling kinetics of the WAP in distilled water and tap water, a simple measurement method was followed. A quantity of 0.1g of dry WAPs was taken in a nylon tea bag and immersed into a 200 mL of beaker with sufficient amount of distilled or tap water. The tea bags were lifted from the distilled and tap water at the predetermined time intervals and drained for 2 minutes. Thereafter, the samples were weighed and the water absorbency at a given time was calculated deducting the weight of the tea bag. In all the cases, three samples are used for repeatability .

Moreover, diffusion behaviour of water into polymer network was analysed from the swelling kinetics result. The swelling kinetics of the WAP in two different solutions including distilled and tap water for CW and FW are presented in **Figure 3.4**. Judging from the curves, it can be observed that the swelling trend of WAP in both the solution was similar. The swelling capacity increased rapidly in the initial stage and then approached a constant equilibrium swelling capacity similar to previous literature (Li et al., 2007; Zhou et al., 2011; Wan et al., 2013). The swelling trend line of the WAP can be expressed as a Voigt-based equation (Zhao et al., 2015).

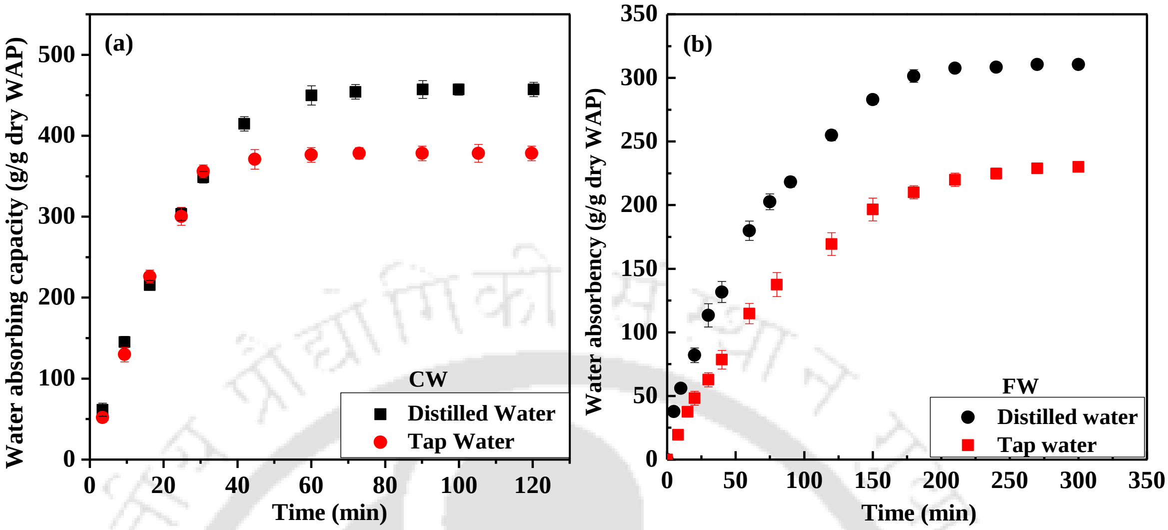


Figure 3.4 Swelling kinetics of (a) CW and (b) FW in distilled and tap water.

$$S_t = S_e[1 - \exp\left(-\frac{t}{\tau}\right)] \qquad \text{Eq. 3.2}$$

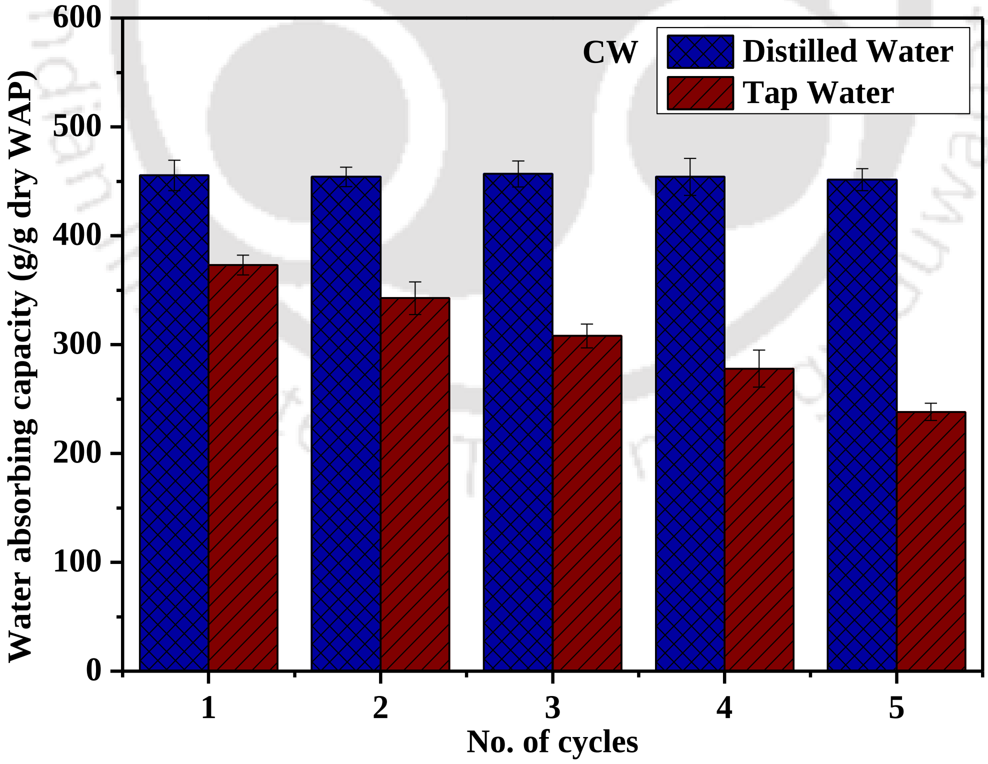
where, S_t is the swelling at time t (g/g), S_e is the equilibrium swelling (g/g), t is the time (h) required for swelling S_t, and τ denotes the rate parameter (h).

The obtained rate parameter of the CW swelling in distilled water and tap water is 1h and 0.45h respectively. And for FW swelling in distilled water and tap water is around 3hrs. The higher rate parameter in distilled water may be a result of presence of hydrophilic group and its electrostatic repulsion in the polymeric network which cause greater osmotic pressure difference whereas in tap water presence of salt increase the ionic strength of the solution resulting reduced osmotic pressure difference between the solution and the polymer network. The larger osmotic pressure difference can cause high rate of water molecules to be absorbed. As the swelling continues, the water molecules penetrates into the polymer network reducing the repulsion force and gradually weekend the osmotic pressure difference. This is why the rate of swelling get reduced after certain period of time and becomes flat reaching to the equilibrium point.

3.3.3) Alternate wetting-drying of WAP and re-swelling capability

Re-swelling capability is one of the most crucial factors for the application of WAP in practical condition. Re-swelling ability of the WAP was investigated through multiple alternate wetting drying cycle and measuring their equilibrium WAC in distilled and tap water. From **Figure 3.5**, a slight decrease in the water absorbing capacity or swelling capacity was noticed after multiple wetting-drying cycle for WAP in distilled water whereas a sharp decrease can be seen for WAP in tap water. Since the swollen WAP was dried in oven, polymer network structure undergoes changes during moisture evaporation causing a decrease in WAC.

However, the sharp decrease in the water absorbency can be due to the presence of salt and other impurities in tap water which affected the polymer chain and weakened the chemical bond between different hydrophilic groups leading to degradation of the polymeric structure. The decrement in WAC for CW and FW in tap water was found to be 36.2% and 25.1% respectively, where WAC decrement in distilled water was only about 2.8% and 5.6%, respectively.



(a)

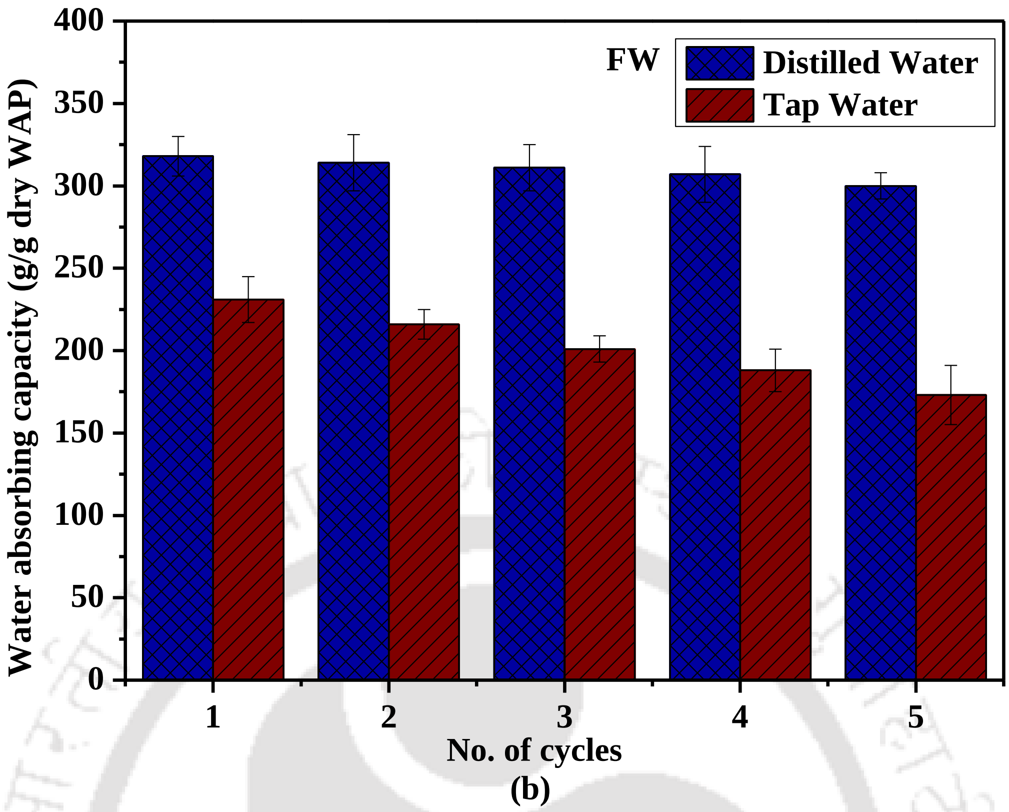


Figure 3.5 Re-swelling ability and degradation properties of (a) CW and (b) FW

3.4) Determination of SWCC

The soil-water characteristics curve (SWCC), which is also known as soil water retention curve (SWRC) is a graphical representation of soil suction or negative pore water pressure variation with water content (gravimetric or volumetric water content or degree of saturation). Gravimetric water content (w) is the ratio of the weight of water to the weight of dry soil, while volumetric water content (θ) is the ratio of the volume of water to the total volume of soil mass and degree of saturation (S) is defined as the percentage of voids filled with water. A typical drying and wetting SWCC is presented in **Figure 3.6.**

Some of the relevant features of the SWCC are as follows:

1. The volumetric water content at saturation, θ_s, describes the water content at which the soil is completely saturated and typically depicts the initial state for evaluating the drying path. It is equal of the porosity of the soil.

2. The air-entry value (AEV), ψ_a, is the suction at which air enters the largest pore present in the soil sample during the drying process (Brooks and Corey 1964). This is the point where the desaturation process starts.

3. Residual water content (θ_r) is the minimum water content below which there is no appreciable change in θ. Suction corresponding to θ_r is called residual soil suction, ψ_r (Yang et al., 2004).

4. The water-entry value, ψ_w, on the wetting SWCC, is defined as the suction at which the water content of the soil starts to increase significantly during the wetting process (Birle et al., 2008).

3.4.1) Measurement of soil suction

There are different instruments available for measurement of suction, but none of them alone can measure the soil suction for the entire range required for establishing SWCC. Measurement of suction is mainly divided into direct and indirect methods for matric and total suction measurements. The commonly used instruments for direct suction measurement are the pressure plate apparatus, tensiometer, suction probe. Indirect suction measuring devices do not measure the pore water pressure directly instead, they measure the soil properties such as the vapor pressure, moisture content, resistivity of the soil, thermal conductivity, electrical conductivity, etc. of the porous medium and correlate it with soil suction with the help of calibration equation (Bulut and Leong 2008; Pan et al 2010). The instrument and technique used in this study for measuring suction are discussed below.

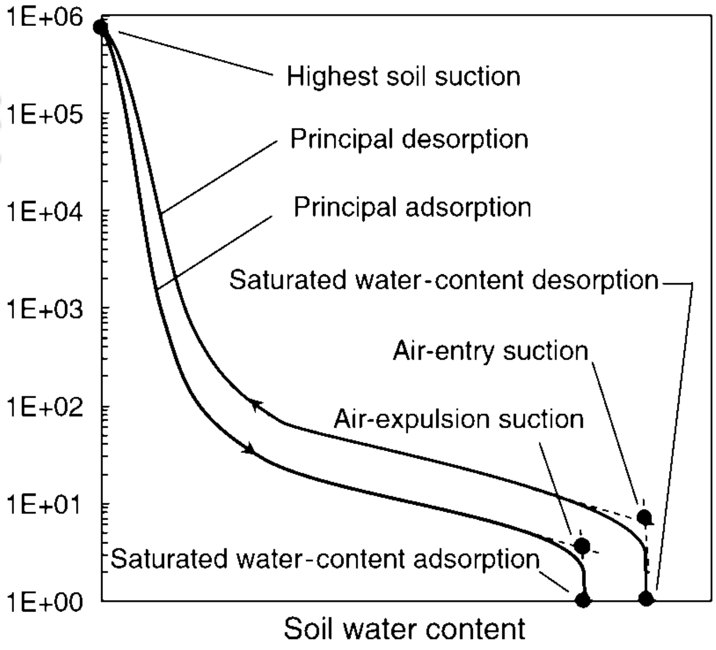


Figure 3.6 SWCC mechanism for a full suction range with hysteretic behaviour (Lu et al. 2015).

3.4.2) T5 tensiometer

The T5 tensiometer as shown in **Figure 3.7** allow the direct and precise measurement of soil suction. The technical specifications of the used sensor, as reported in the operator's manual, are listed in **Table 3.3.** The intended use of tensiometers is the measurement of matric suction in the range of 0 kPa to -100 kPa (suction/soil water tension). For convenience, the negative sign is not used further in the explanation.

When the tensiometer is inserted into soil for suction (ψ_m) measurement, the water present in the shaft tries to equilibrate with the suction present in the soil-water via the ceramic interface. For an efficient equilibrium, the continuity of water between the shaft and soil-water becomes extremely important. The continuity ensures that the negative pressure of soil-water will be identical with the water tension developed in the shaft. The changes in water tension in the shaft water result in the deformation of the silicon chip. The silicon chip is thin and therefore extremely sensitive to such pressure (water tension) variations. The strain or deformation of the silicon chip induces a change in its specific electric resistance, which is converted to a defined voltage signal. The changes in water tension in the shaft are captured electronically and converted to pressure which offers a continuous measurement of suction.

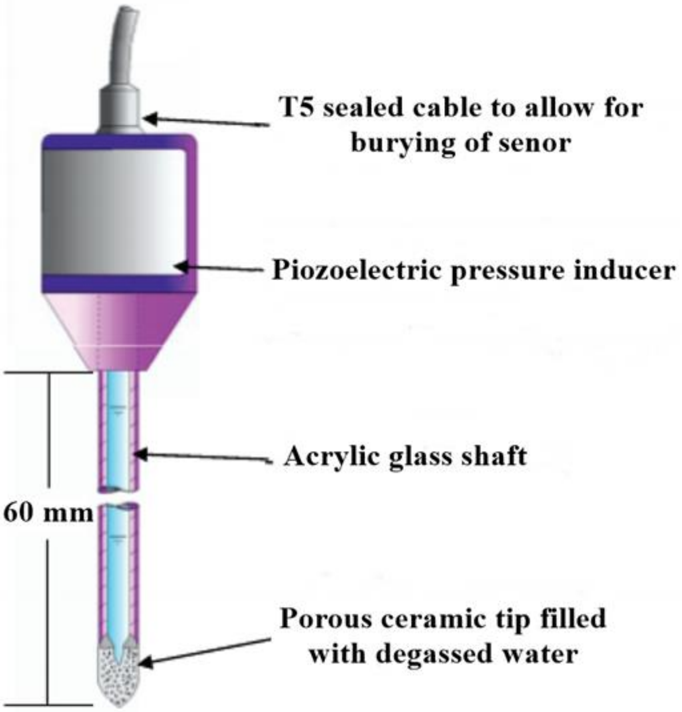


Figure 3.7 Details of T5 tensiometer

Table 3.3: Technical specifications of T5 tensiometer

Measurement	Matric potential (ψ_m)
Measurement range	(ψ_m): +100kPa to – 85 kPa
Accuracy	(ψ_m): ±0.5 kPa
Resolution	(ψ_m): 0.1 kPa
Operative temperature	4° C to 70° C
Equilibrium time	10 seconds
pH range	pH 3 to pH 10
Compatible data logger	DL6 Data logger

3.4.3) Matric potential sensor (TEROS21)

TEROS21 measures the water potential and temperature of the soil and other porous materials. These sensors have a low power requirement, making them ideal for permanent burial in the soil and continuous reading with a data logger or periodic reading with a handheld reader. The TEROS21 has a six-point calibration that results in research-grade accuracy. The TEROS21 sensors measure a wide range of soil water potentials without user maintenance and factory calibration. The technical specifications of the used sensor, as reported in the operator's manual, are listed in **Table 3.4**. Unlike tensiometers, which need a skilled operator, this dielectric water potential sensor needs no maintenance. The added temperature measurements can be used to determine approximate soil water potential in frozen soils.

A dielectric matric potential sensor, TEROS21 (METER Group, USA), as depicted in **Figure 3.8** was used in the present study to measure the suction. The sensor consists of two engineered ceramic disks sandwiched between two stainless steel screen and a circuit board. When TEROS21 inserts into the sample, the water present in the sample tries to equilibrate with the two ceramic disks. The TEROS21circuit board comprises an oscillator that generates an electromagnetic (EM) field during suction measurement. The EM field charges the ceramic disks around the TEROS21 circuit board. This stored charge is proportional to dielectric permittivity (ε) of the ceramic disks and measures the water content of the ceramic disk. The matric suction was found out from the previously established suction-water content relationship of the ceramic disk.

Table 3.4: Technical specifications of TEROS 21

Measurement	Matric potential (ψm), Soil temperature
Measurement range	(ψm): -9 to -100,000 kPa, Soil temperature: -40° C to 60° C
Accuracy	(ψm): ± (10% of reading) from -9 to -100 kPa Soil temperature: ± 1° C
Resolution	(ψ_m): 0.1 kPa, Soil temperature: 0.1° C
Operative temperature	-40° C to 60° C
Equilibrium time	10 min to 1 hour depending on matric potential
Measurement speed	150 ms (millisecond)
Sensor type	Frequency domain with calibrated ceramic discs, thermistor
Compatible data logger	DL6 Data logger

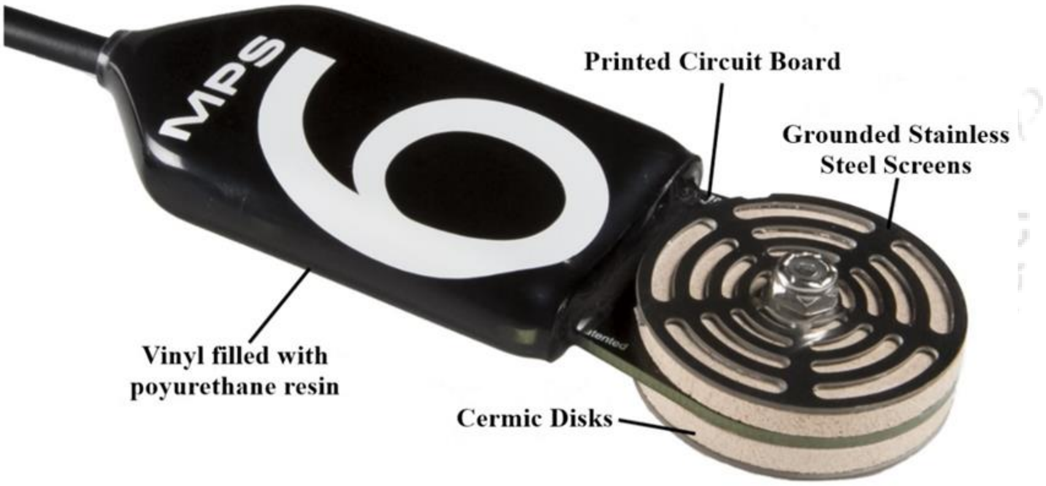


Figure 3.8 Details of TEROS21 senor

3.4.4) Measurement of soil moisture content

Measurement of soil volumetric moisture content (θ) is vital for establishing the SWCC. A 5TM moisture content measurement sensor (developed and supplied by Meter Group Inc., USA) as shown in **Figure 3.9** is used in this study. The 5TM sensor incorporates a temperature reading into the traditional soil moisture sensor. The θ is obtained by measuring the dielectric constant of the media through the utilization of capacitance/frequency domain technology while the temperature is measured using an onboard thermistor. 5TM sensor incorporates a high-frequency oscillation, which allows the sensor to accurately measure soil moisture in any soil or soilless media with minimal salinity and textural effects.

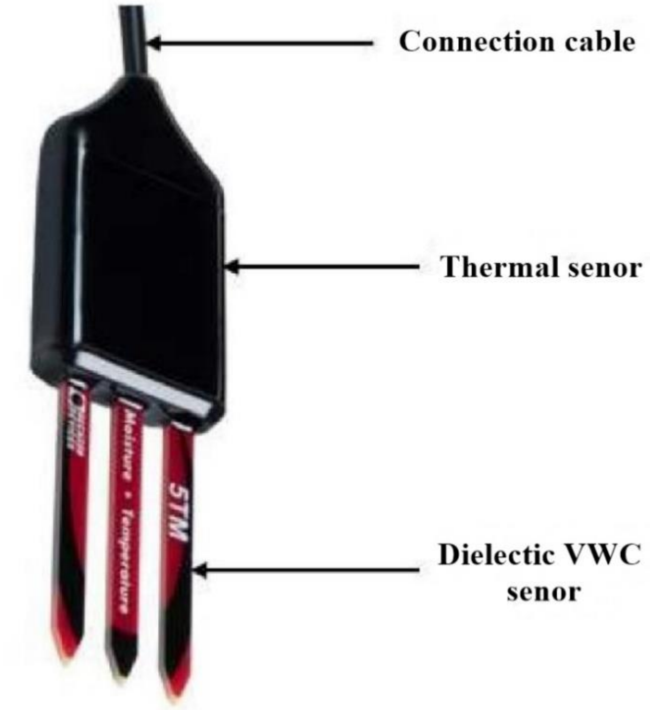


Figure 3.9 Details of 5TM senor

The dielectric permittivity of soil changes with the water content of the soil. The value of dielectric permittivity of water is 80, while for dry soil and air it is around 4 and 1, respectively. This broad range of permittivity helps in measuring the θ of soil from saturated to dry state conditions. The sensor is equipped with an oscillator working at a frequency of 70 MHz, which generates an electromagnetic field. The electromagnetic field charges the soil around the probe. This stored charge is proportional to permittivity and θ and is measured by the copper traces of the prongs. The 5TM microprocessor outputs a value of dielectric permittivity from the sensor. The dielectric permittivity was converted to the θ by Topp's equation.

3.5) Measurement of stomatal conductance

Stomatal conductance (SC) is a function of the density, size, and degree of opening of stomata, pores in plants that open to the outside air. The Leaf Porometer measures SC by placing the conductance of a leaf in series with two known conductance elements and comparing the humidity measurements between them. It is a battery- operated, a menudriven device used to measure stomatal conductance of leaves. It can display information in three selectable units:

1. mmol/m^{2}s – stomatal conductance (millimoles per meter squared seconds)

2. m^{2}s/mol – stomatal resistance (meters squared seconds per mole)

3. s/m – stomatal resistance (seconds per meter)

The Leaf Porometer cannot take measurements without the aid of the sensor head. This sensor head is responsible for gathering the information (vapor pressure, humidity, etc.). **Figure 3.10** shows the external components of the sensor head and leaf porometer.

(a)

(b)

Figure 3.10 (a) External components of the sensor head and (b) leaf porometer

3.6) Measurement of photosynthetic yield

The photosynthetic yield (PY) analyzer MINI-PAM-II has been designed for the highly sensitive saturation pulse analysis of photosystem II (PS II) for the field and the laboratory conditions. The major technological advancements of the MINI-PAM-II are the consistent use of energy-efficient LEDs, an internal PAR sensor, and stand-alone operation by a well-readable touchscreen under natural light conditions. The MINI-PAM-II device records only the fluorescence elicited by measuring light. Fluorescence excited by internal actinic light or saturation pulses, and it is not measured external light, like solar radiation. Therefore, the MINI-PAM-II determines how environmental factors modulate the efficiency of conversion of measuring light into fluorescence. Measurements under field conditions are easily controlled and monitored by a touchscreen. The DLC-8 leaf clip permits dark-acclimation of small leaf areas in the field, essential for the proper determination of the maximal quantum yield Fv/ Fm and recoding of dark-light induction kinetics. **Figure 3.11** shows the DLC-8 dark leaf clip and MINI-PAM-II.

3.7) Data storing device

The Em50 is a 5-port, self-contained data logger especially suited for field research and commercial agriculture. The sensors are plugged into the 5 channels and measured as directed by the user. The Em50 is ideal for long-term outdoor use. Software ECH2O Utility normally converts the raw data of recorded by the Em50 into engineering units appropriate for the sensor while downloading. The Em50 data logger is shown in **Figure 3.12.**

(a)

Figure 3.11 (a) DLC-8 dark leaf clip and (b) MINI-PAM-II

Figure 3.12 Datalogger Em50

Chapter 4

Combined influence of fertilizer and WAP on SWCC

4.1) Introduction

Shortage of irrigation water along with the drastic weather changes significantly affects agricultural productivity. Ensuring food security for all is a challenging issue under the current scenarios of global climate change, shortage of rainfall, and water stress conditions. A more structured and engineered approach is required to mitigate the negative impacts of water stress. Engineering the water retention by using appropriate soil amendments could be one of the possible solutions to minimize the water stress condition in crop species and reduce downward infiltration of excess water (Huettermann et al., 2009; Abobatta, 2018; Sreedeep et al., 2019; Saha et al., 2020a). The addition of hydrophilic polymers, such as superabsorbent hydrogel (SAH) or water-absorbing polymer (WAP), improve the soil pore volume and increase the water holding capacity of soil due to their high-water absorbency (Narjary et al., 2012; Wei and Durian, 2013; Saha et al., 2020c; Saha et al., 2021a). These WAPs can absorb and store water more than five hundred times their own weight due to the several hydrophilic functional groups attached to their structure (Feng et al., 2014). WAP's performance is sensitive to salt solutions and other impurities, as the presence of monovalent and multivalent ions in the swelling medium reduces their water absorbency (Zhu et al., 2015; Sultana et al., 2018; Saha et al., 2020d). Therefore, it is important to understand the water absorbency of WAP in different swelling mediums before field applications.

Inorganic and organic fertilizers are an integral part of agricultural practices for meeting the essential nutrients required to improve plant growth and crop yield. Past studies have reported that the combined use of organic and inorganic fertilizers provide better performance in terms of crop growth and crop yield as compared to inorganic fertilizers only (Sarwar et al., 2008; Zhang et al., 2016; Subhan et al., 2017; Zhou et al., 2017; Mi et al., 2018). It is hypothesized that the application of fertilizers may inhibit the performance of WAP due to its sensitivity to ionic solutions (Laftah et al., 2011). Most of the previous studies explored WAP implementation in different soil textures (Agaba et al., 2010; Narjary et al., 2012; El-Asmar et al., 2017; Saha et al., 2020a). There are studies in the literature that investigated the effect of different fertilizers and the fertilizer amendment rate on the soil properties and crop growth indices without WAP amendment (Adugna, 2016). However, the impact of fertilizer application on WAP performance and its combined (fertilizer + WAP) influence on the water retention property of soil is unclear. The water retention property is quantified in terms of soil water characteristics curve (SWCC), which is the graphical representation of volumetric water content variation with soil suction (or negative pore water pressure) (Saha and Sekharan 2021). The knowledge of SWCC is central to understanding how easily the water is lost from the soil during drying. It is an essential input function for irrigation water requirement, irrigation scheduling, solute/ nutrient transport through the soil, and predicting unsaturated hydraulic conductivity (Li et al., 2016; Leong, 2019).

Therefore, it is important to investigate the influence of organic and inorganic fertilizers on the performance of WAP amended soils. Such a study is essential for developing the best management practices of using WAP in soil. Keeping this in view, a systematic study was planned to understand the soil-water-WAP-fertilizer interaction under water stress conditions. The primary objective of this study is to evaluate the performance of two different WAPs (a commercially available WAP and a laboratory synthesized WAP) in the presence of organic and inorganic fertilizers for two agricultural soils (silt loam and silt). The variation in performance of WAP was quantified in terms of WAC and SWCC.

4.2) Materials and methodology

4.2.1) Materials

Two different textured soils were collected from the north-eastern region of India. The agricultural soil (AS) was collected from Kamrup district, Assam, India, while the Brahmaputra silt (BS) was collected from the Brahmaputra river bank, near the Indian Institute of Technology (IIT) Guwahati, Assam, India. Two different WAPs, which include commercially available water-absorbing polymer (CW) and a laboratory synthesized fly ash modified water-absorbing polymer (FW) (Saha et al., 2020d), were used in this study. The details characterization of soils and WAPs were presented in Chapter 3.

Two inorganic fertilizers (urea and DAP) and one organic fertilizer (cow manure) were used in this study, which are frequently utilized in agriculture. The Hindalco-produced diammonium phosphate (DAP) fertilizer, with 18% nitrogen (N) and 46% P_2O_5, is the most popular phosphatic fertilizer because of its high nutrient content. DAP can be easily handled and stored well. This is likely due to its physical properties such as particle size, particle density, bulk density, particle shape, and flowability which directly affect the quality of spread of granular fertilizer. Urea is a common nitrogen source in all solid nitrogenous fertilizers, and its standard crop-nutrient rating (NPK rating) is 46-0-0.

Cow dung is a waste material of bovine animal species. It is high in organic materials, rich in nutrients, and readily available in the local market. In general, it contains about 3 percent nitrogen, 2 percent phosphorus, and 1 percent potassium (3-2-1 NPK). The present study used a low-cost laboratory-developed WAP (FA-WAP) along with a commercial WAP (Magic hydrogel), which is easily available in the market. Therefore, the selection of WAP is based on cost and availability in local market. Similarly, low-cost fertilizers that are easily available in market were selected. Inorganic fertilizer (urea and DAP) and organic fertilizer (cow manure) were adopted for investigation in this study.

The field emission scanning electron microscope (FESEM) images of the treated soils were obtained using Gemini 300 (Carl Zeiss, Germany). Prior to FESEM analysis, the soil samples were oven-dried to avoid sample charging, and placed on the aluminium stubs over the double-sided carbon tape. FESEM images show the microstructural changes in the soil pores due to the addition of different combinations of WAP and fertilizers.

4.2.2) Methodology

4.2.2.1) Water absorbing capacity (WAC) of WAP in the presence of fertilizers

The WAC of both the WAPs was determined in different fertilizer solutions. For this purpose, different concentrations of fertilizer solutions (5 g/l, 10 g/l, 25 g/l, 50 g/l, and 100 g/l) were prepared by adding the three different fertilizers (organic, urea, and DAP) in 500 ml of distilled water. As reported in the literature, the gravimetric method (Witono et al., 2014; Saha et al., 2021b) was used to determine the WAC of WAP. One gram of dry WAP was placed in a nylon tea bag and immersed into the fertilizer solutions. The WAP was allowed to swell till it reached its swelling equilibrium. The nylon teabag was lifted for draining out the excess solution through its pores under gravity. After draining of excess solution, the weight of the swollen WAP was measured. For accurate measurement of water absorbency of WAP, the solubility of the fertilizers was evaluated, which was found to be 9%, 57%, and 97% for organic fertilizers, DAP, and urea, respectively. The weight of the insoluble fertilizer was deducted from the swollen WAP weight, and the water absorbency of WAP was calculated.

The present study used an alternate approach to measure the decrement in water absorbency of WAP, when it interacts with the fertilizer. In this approach, one-gram WAP particles in a nylon bag was immersed in 500 ml of distilled water and allowed to reach the maximum swelling equilibrium (maximum water absorbing capacity). The required quantities of fertilizers were then added to the distilled water (mixed thoroughly) in which the swollen WAP was placed. After sufficient interaction time (6 hours based on trial experiments), the excess water was removed from the swollen WAP, and the weight was measured. The water absorbency of the WAPs, as obtained from both approaches, was compared to evaluate the influence of fertilizer on the swelling characteristics of WAP. A dimensionless sensitivity factor (*f*) was calculated using Eq. 4.1 to compare the water absorbency of WAPs in the presence of different fertilizers. A low value of *f* indicates lower influence of fertilizer on the WAC of WAP.

$$f = 1 - \frac{Water\ absorbency\ in\ presence\ of\ fertilizer}{Water\ absorbency\ in\ distilled\ water} \qquad \text{Eq. 4.1}$$

4.2.2.2) Measurement of soil-water characteristics curve (SWCC)

The soils were mixed in dry state in different proportions with WAP and fertilizers. A total of thirteen combinations of treatments (T0 to T12) were considered, as listed in **Table 4.1.** The combinations were decided in such a manner that the specific and combined effect of fertilizers and WAPs on SWCC of soil can be quantified. As shown in **Table 4.1**, bare soil (T0) was used as the control for determining reference SWCC. The effect of only fertilizers on SWCC was explored by T1 and T2 and only WAP by T3 and T8. All other combinations portrayed the combined influence of fertilizers and WAPs. The amendment rate of the WAP (0.2% of the dry mass of soil check) was selected based on the previous studies (El-Asmar et al., 2017; Saha et al., 2020a; Saha et al., 2021a). It was noted from the previous studies that the fertilizer amendment rate could vary depending on the soil texture, crop species, and climatic conditions. Most of the previous studies used 100-150 kg/ha of inorganic fertilizers and 1000-1100 kg/ha of organic fertilizers under field conditions (Chang et al., 2007; Kumar et al., 2014; Alhasan et al., 2020). The present study used the amendment rate of inorganic fertilizers as 4% (for both urea and DAP) and organic fertilizer as 10% of the dry weight of the soil. These amendment rates are considered as the maximum permissible limit for fertilizer application in pot experiments, and hence the worst possible influence on WAP can be estimated.

The dry soil samples with different quantities of WAP and fertilizers were hand compacted [close to field conditions] in a bottom-perforated pot (for free drainage), as shown in **Figure 4.1**. The whole setup was placed in controlled laboratory conditions with an average temperature of 25° C and relative humidity of 50%. First, the soil samples were irrigated with sufficient water to ensure near saturation and negligible matric suction. A filter paper was placed at the bottom of the pot to restrict the migration of fine soil particles during irrigation.

Table 4.1. Details of different combinations of water-absorbing polymer (WAP) amended soil for measuring soil-water characteristic curve (SWCC)

Treatments	Description	Soil (kg)	WAP		Fertilizer		
			CW (g)	FW (g)	Organic (g)	Urea (g)	DAP (g)
T0	Bare Soil (control)	2	-	-	-	-	-
T1	Soil + Organic + Urea	2	-	-	200	80	-
T2	Soil + Organic + DAP	2	-	-	200	-	80
T3	Soil + CW	2	4 (0.2%)	-	-	-	-
T4	Soil + CW + Organic	2	4 (0.2%)	-	200	-	-
T5	Soil + CW + Organic + Urea	2	4 (0.2%)	-	200	80	-
T6	Soil + CW + Organic + DAP	2	4 (0.2%)	-	200	-	80
T7	Soil + CW + Organic + Urea + DAP	2	4 (0.2%)	-	200	80	80
T8	Soil + FW	2	-	4 (0.2%)	-	-	-
T9	Soil + FW + Organic	2	-	4 (0.2%)	200	-	-
T10	Soil + FW + Organic + Urea	2	-	4 (0.2%)	200	80	-
T11	Soil + FW + Organic + DAP	2	-	4 (0.2%)	200	-	80
T12	Soil + FW + Organic + Urea + DAP	2	-	4 (0.2%)	200	80	80

The SWCCs of the samples were measured by continuously monitoring soil matric suction and volumetric water content during drying (imposed drought) period. TEROS21 (METER Group, Inc., USA), a matric potential sensor, was used in this study for measuring matric suction (ψ_m). In addition, a miniature tensiometer (T5), manufactured by UMS GmbH, Munich, Germany was also utilized for measuring matric suction. T5 tensiometer is known to measure suction reliably till 80 kPa. On the other hand, a factory-calibrated TEROS21 can accurately measure ψ_m up to a value of 2000 kPa (Saha et al., 2020b). The combined use of both TEROS21 and T5 permits a wide range of suction measurement for establishing SWCC. The volumetric water content (θ), which is the ratio of the volume of water to the total volume of the soil sample, was measured using the 5TM sensor (developed and supplied by Meter Group Inc., USA).

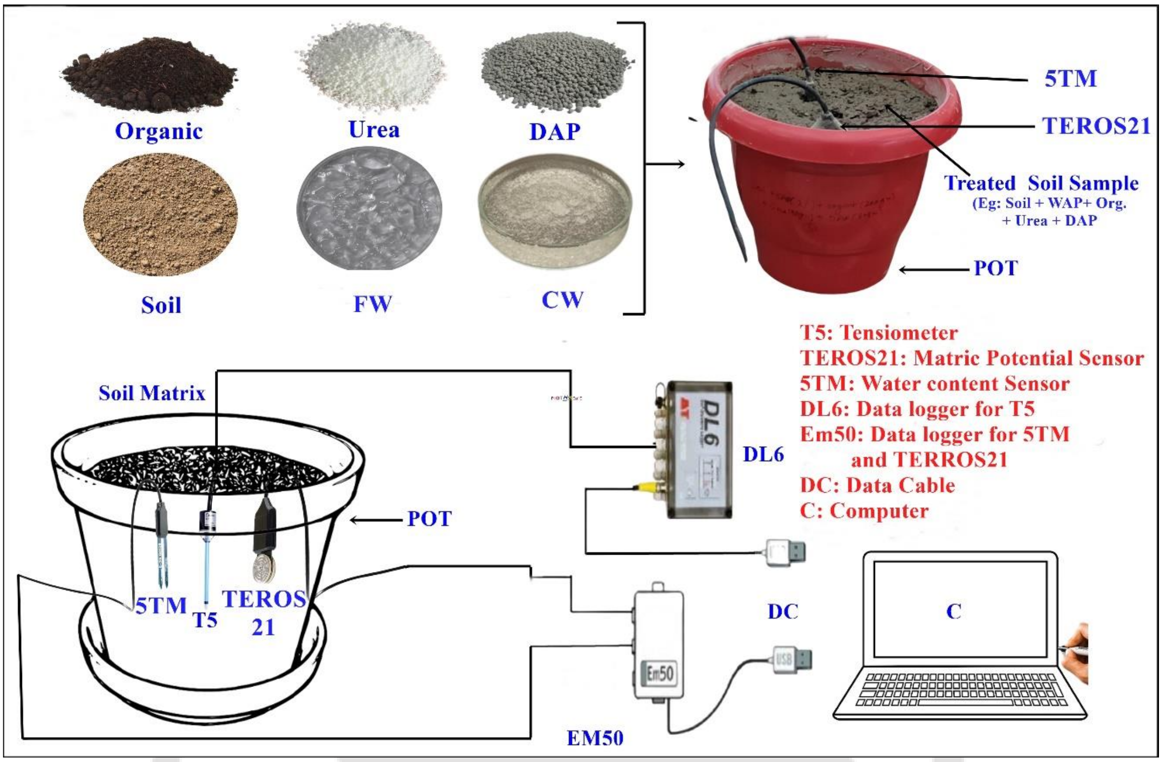


Figure 4.1 Experimental methodology to establish soil-water characteristics curve (SWCC) of water-absorbing polymer (WAP) and fertilizer amended soils

4.2.3) Statistical analysis

The WAC measurements in different fertilizer solutions were performed in triplicate to ensure repeatability of the dataset. Three identical solutions were prepared for every fertilizer solution, and the standard deviation (SD) was determined. A two-way analysis of variance (ANOVA) test was conducted to quantify the significant influence of fertilizer concentrations and fertilizer type on the WAC of WAP. A similar study was also performed for analyzing the interaction of soil texture and WAP treatments on the SWCC parameters. ANOVA models were coupled with Tukey's HSD test to detect the mean statistical differences (Nassaj-Bokharaei et al., 2021; Melo et al., 2019). Mean differences were considered significant at *p*-value <0.05.

4.3) Results and discussion

4.3.1) Effect of fertilizer on water absorbency of WAP

Figures 4.2(a) and (b) show the effect of different fertilizers (organic, urea, DAP) on the water absorbency of both WAPs (CW and FW). The addition of both organic and inorganic fertilizers has decreased the water absorbency of the WAPs, and the decrement is proportional to fertilizer concentrations. It can be noticed that both the approaches (i.e., dry WAP added in fertilizer solutions and dry fertilizers added to distilled water containing swollen WAP) gave almost identical results. This suggests that the sequence in which WAPs and fertilizers are added, does not influence the equilibrium value of water absorbency. A significant reduction in water absorbency of WAPs is observed in DAP corresponding to a fertilizer concentration of 5 g/l. After that, the decrease in WAC of both WAPs with an increasing DAP concentration was not significant (p-value >0.05). It can be noted that DAP is an ionic compound, and the reduction in water absorbency of WAP is attributed to the osmotic pressure differences between the WAP network and DAP solutions. The WAP particles consist of several deprotonated carboxyl groups (COO^-), which create anion-anion repulsive force inside the polymer network (Feng et al., 2014). After the addition of WAP in distilled water, a considerable osmotic pressure difference develops between polymer network and distilled water, which leads to the absorbing of water molecules inside WAP particles (Zhang et al., 2014). The presence of DAP increases the ionic strength of the solution, which reduces this osmotic pressure difference and subsequent reduction in water absorbency. On the other hand, there is a minimal reduction in water absorbency of WAP in urea solution as compared to other fertilizers due to its non-ionic nature. Based on the statistical significance test, the influence of urea on WAC was found to be significant as compared to distilled water, when its concentration exceeds of 50 g/l for CW and 25 g/l for FW. The organic fertilizer significantly influenced the WAC of CW and FW up to a concentration of 25 g/l and 5 g/l, respectively, followed by a minimal decrement in WAC with increasing organic fertilizer content. The organic fertilizer contains various ionic and non-ionic impurities, which can interact with the WAP, resulting in a higher decrease in water absorbency than urea (Gupta et al., 2016).

For comparing the sensitivity of two WAPs to different fertilizers, the sensitivity factor (*f*) was calculated using Eq. (1) and plotted **in Figure 4.2 (c)**. The use of *f* is important because the maximum swelling capacities of the WAPs are different, and hence the water absorbency in the presence of fertilizer should be normalized. The sensitivity factor is calculated from the average value of water absorbency of WAP (as obtained using the two approaches) in the presence of different fertilizers. It may be noted that the lower value of the sensitivity factor indicates lesser influence on water absorbency. The sensitivity of both WAPs to non-ionic urea fertilizer is less and comparable. The sensitivity of WAPs to organic fertilizer is higher than the urea and has comparable *f*. For ionic DAP fertilizer, the

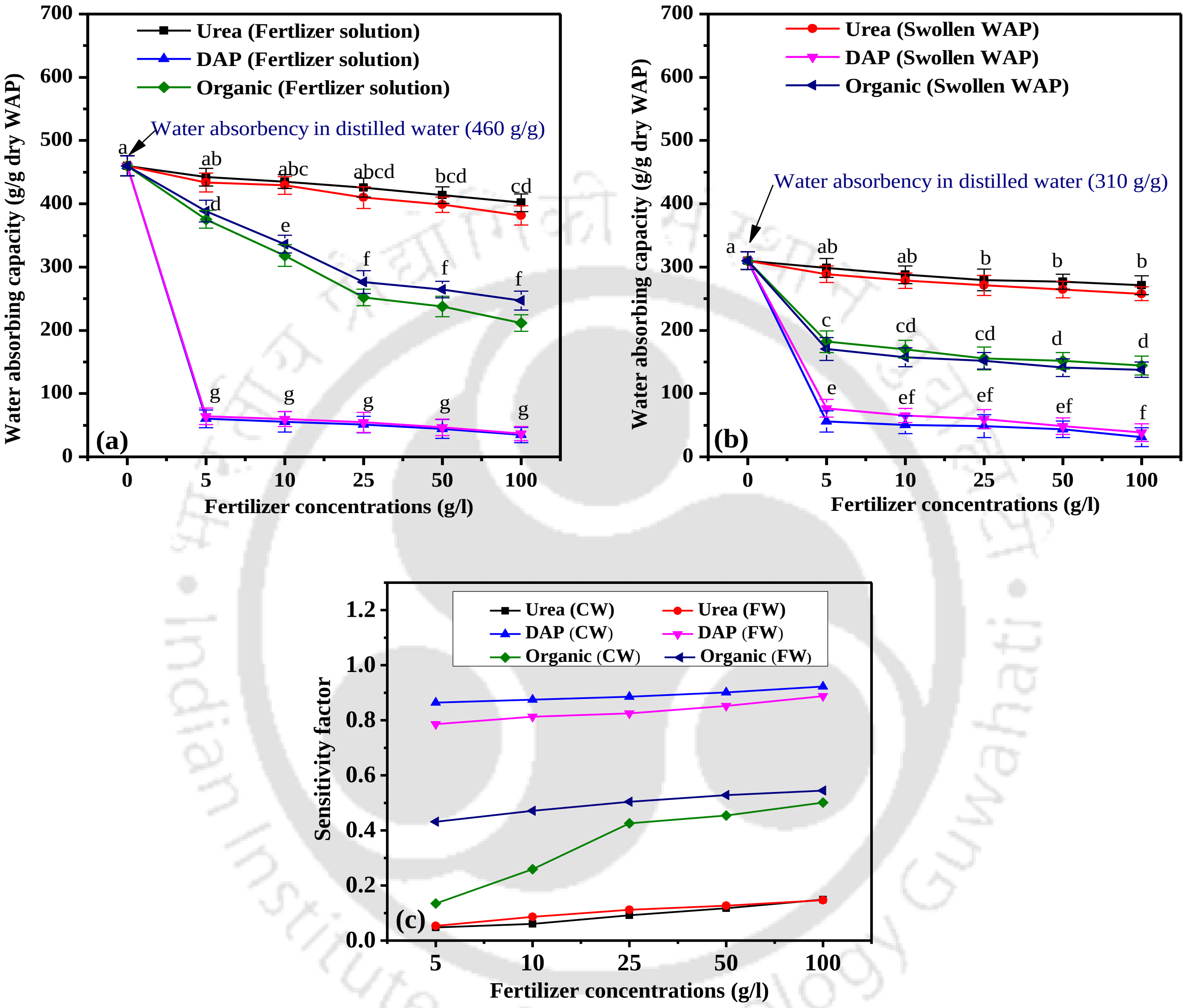


Figure 4.2 Influence of different organic and inorganic fertilizers on the water absorbency of (a) commercial water-absorbing polymer (CW), (b) fly ash water-absorbing polymer (FW), and (c) sensitivity factor of WAPs to different fertilizers. [Note: For Figure (a) and (b), different alphabet indicates significant difference (at p≤0.05) between treatments]

sensitivity of CW is higher than FW. This may be attributed to the inclusion of fly ash as a support material. This observation is in good agreement with past studies (Bao et al., 2011; Zhou et al., 2011), which reported that inclusion of support materials (i.e., clay, starch, cellulose) onto the polymer network could reduce the salt sensitivity and increase the thermal stability of WAPs.

4.3.2) Influence of fertilizer on SWCC of soil

Figures 4.3 (a) and (b) show the combined effect of organic and inorganic fertilizers on SWCC of silt loam and silt, respectively. The fertilizer amendment has improved the water retention behavior of the soils at a higher suction range (> 100 kPa). The addition of fertilizer has minimal effect on the SWCC of soil in the lower suction range (ψ_m <100 kPa). The literature reports that the sole use of inorganic and organic fertilizers has no significant improvement in soil physical properties and soil water holding capacity (Bhatiya and Shukla, 1982; Laxminarayan, 2006). The combined use of inorganic and organic fertilizers can enhance various soil physical properties, such as bulk density, porosity, organic matters, macro-aggregates, and aggregate stability, which may increase the water retention of soil (Blanco-Canqui et al., 2014; Sainju et al., 2003; Subhan et al., 2017). It can be further observed from the Figures that the incorporation of DAP along with organic fertilizer increased the water retention marginally as compared to the urea and organic fertilizers. This can be attributed to urea's higher solubility and mobility than DAP. Fertilizer, that is not soluble in water is likely to remain as solid, thereby altering the pore size and the SWCC. Certain fertilizers such as DAP helps to maintain the available water retention of the soil and hence, facilitating in drought management.

4.3.3) Influence of different WAPs on SWCC of soil

The measured SWCC of silt loam and silt mixed with CW and FW are presented in **Figure 4.3 (c) and (d)**. The Figures indicate a significant improvement in water retention of soil with both WAPs. The increase in water retention was found to be more in silty soil than the silt loam. This can be attributed to the lower clay content (negatively charged particle) and electrical conductivity (EC) of silt as compared to the silt loam (refer Table 3.2 (chapter 3)). The swelling behavior of the WAP is sensitive to the ionic concentration (high EC) of the swelling medium. Hence, soils with higher clay content and EC can restrict the swelling of WAP, leading to lower improvement in water retention (Saha et al., 2020a; Saha et al., 2021b). Moreover, the improvement in water retention is higher in the lower suction range (ψ_m <100 kPa) as compared to the higher suction range (ψ_m >100 kPa). Such an

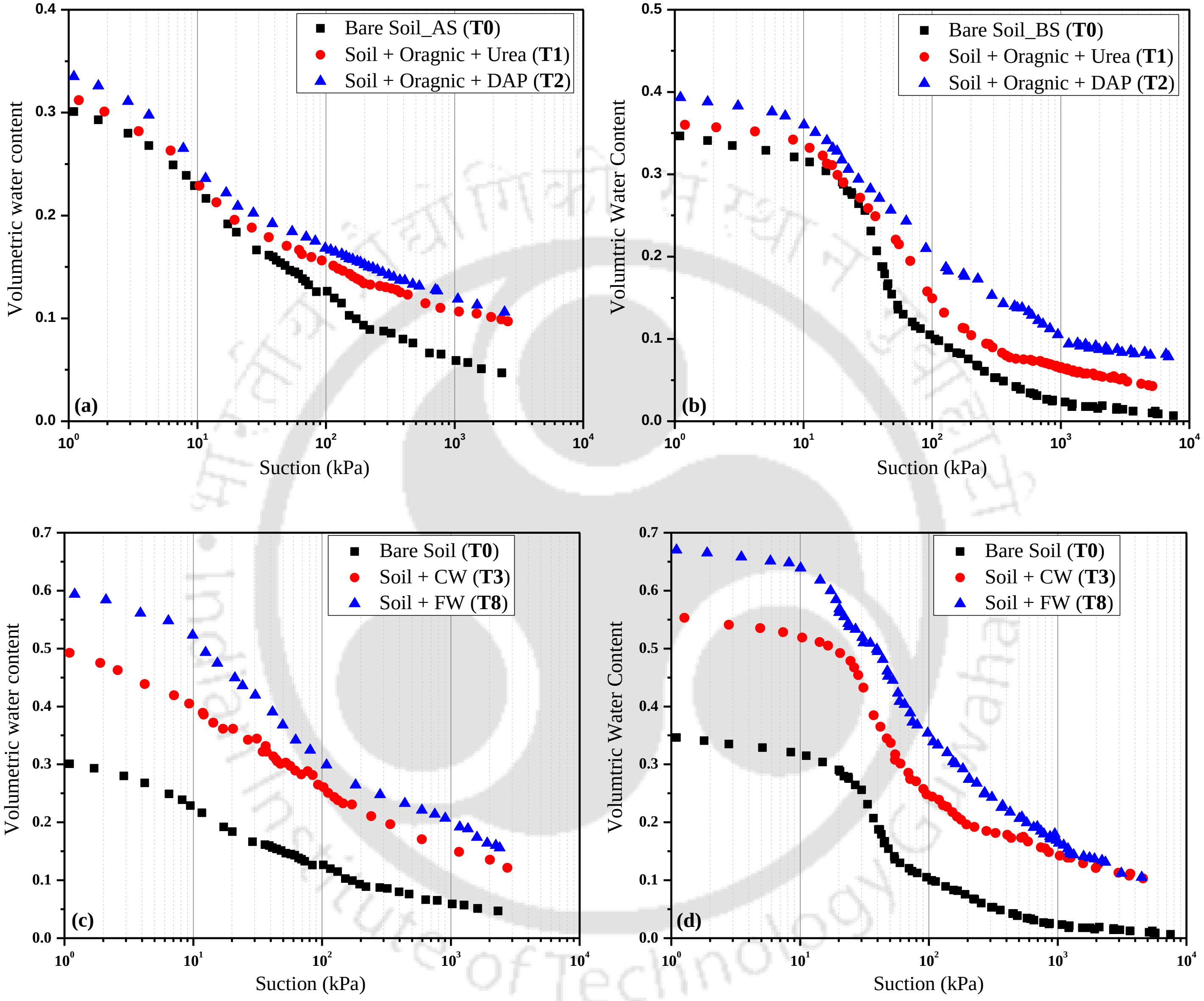


Figure 4.3. Effect of different combinations of fertilizers on soil-water characteristics curve (SWCC) of (a) silt loam and (b) silt, and effect of different water-absorbing polymer (WAP) on SWCC of (c) silt loam and (d) silt

improvement is beneficial for plant growth. The capillary force controls the water retained in the lower suction range, which primarily depends on the soil particle size and pore size distribution. This indicates improved soil pore volume and water storage with the WAP amendment.

The WAP particles occupy the empty pore spaces inside the soil matrix and swell due to water absorption, resulting in higher water retention characteristics in the low suction range (Bian et al., 2018; Rahmati et al., 2019). This observation agrees with the previous studies (Narajry et al., 2012; Saha et al., 2020a Zheng et al., 2020; Womack et al., 2022), which reported a reduction in macro and mesopores of soil with WAP addition. On the other hand, the water retention behavior of soil in the higher suction range is primarily controlled by the specific surface area, soil mineralogy, and water bonding mechanism. The improvement in water retention behavior in the higher suction range may result from the increased surface area of soil due to WAP addition (Dorraji et al., 2010). Moreover, the water stored inside the WAP network is present in the form of bound water (through hydrogen bond), which is only extractable at a higher suction value ($\psi_m > 10^4$ kPa). Some improvement in the water retention can be observed in the higher suction range (100 kPa< ψ_m < 2000 kPa). However, this improvement was not at par with the improvement noted in the lower suction range. Such an improvement in water retention of soil with WAP amendment leads to higher soil-water storage, providing the stored water to plant roots for a prolonged duration under drought conditions.

Comparing the performance of both WAPs, the FW amended soils have higher water retention capacity than the CW amended soils for both soil textures (silt loam and silt). It may be noted that the water absorbency of CW is more than FW in distilled water under free swelling conditions (CW has a water absorbency of 460 g/g, whereas FW has a water absorbency of 310 g/g). **Figures 4.3 (c) and (d)** suggest that FW have performed better inside the soil matrix than CW. Higher water absorbency of WAP may not necessarily translate to higher water retention in soils. One of the possible reasons could be a higher absorbency under load (AUL) [Lejcuś et al., 2018; Misiewicz et al., 2019] of FW than CW. The results reported by Lejcus et al. (2018) revealed that water absorbency of WAP decreases due to the self-weight of soil with an increasing soil depth. This reduction in water absorbency can be more than two times at a soil depth of 10 cm. The addition of inorganic materials, especially aluminosilicate materials (e.g., bentonite, kaolin, montmorillonite) in the WAP network can improve the mechanical properties (such as gel strength, elastic modulus, AUL) of WAP composite (Zohuriaan-Mehr and Kabiri 2008;

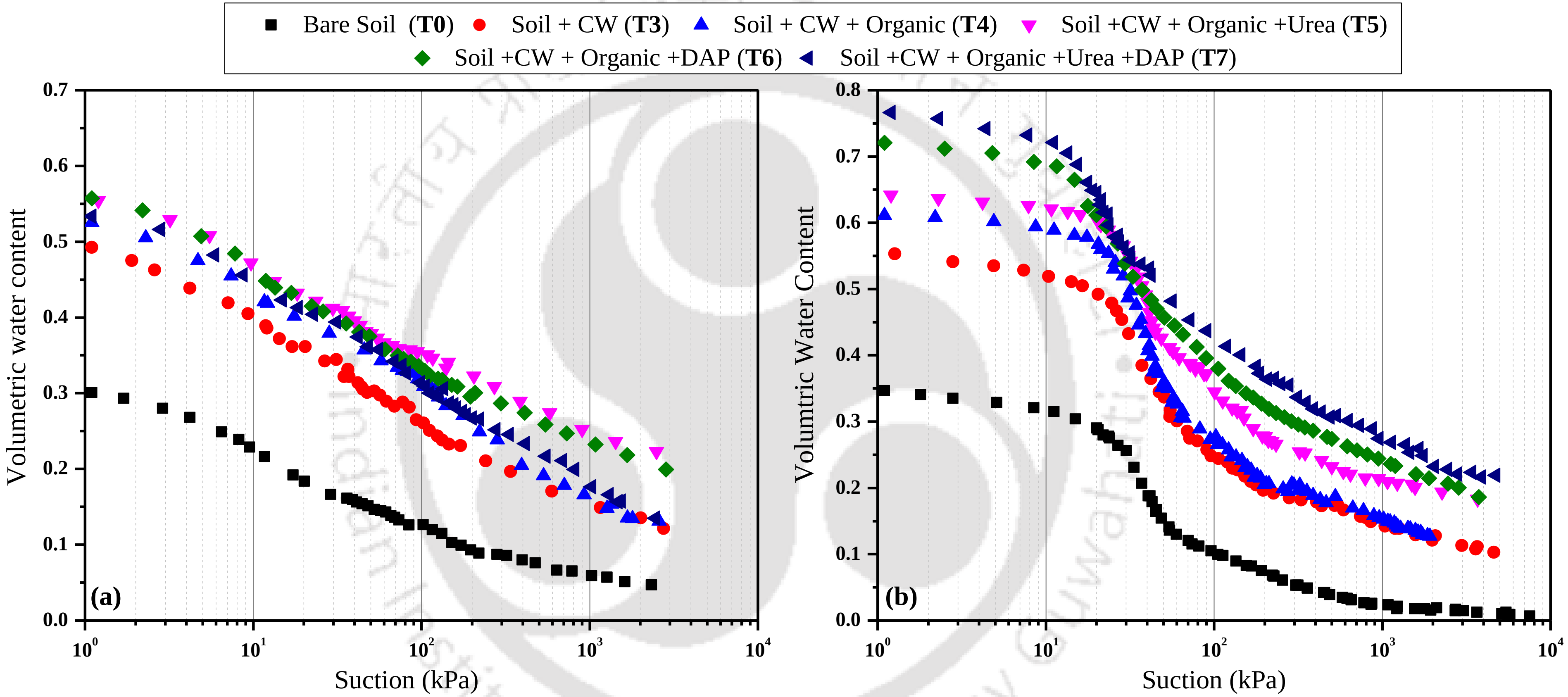


Figure 4.4. Effect of various treatments of commercial water-absorbing polymer (CW) and fertilizers on the measured soil-water characteristics curve (SWCC) of (a) silt loam and (b) silt

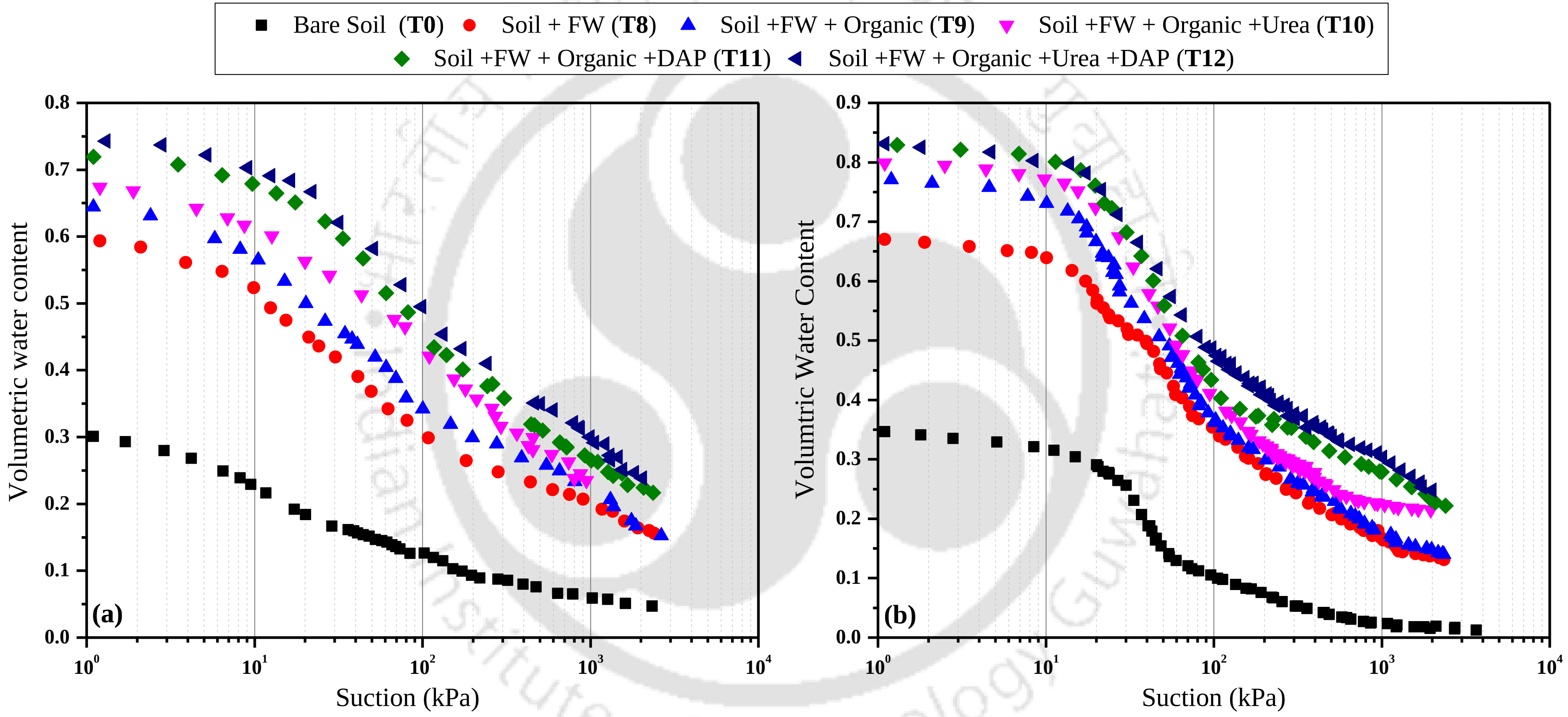


Figure 4.5. Effect of various treatments of fly ash water-absorbing polymer (FW) and fertilizers on the measured soil-water characteristics curve (SWCC) of (a) silt loam and (b) silt

Kabiri et al., 2011). In the present study, the FW was developed by incorporating aluminosilicate material (fly ash) into the WAP network, which is capable of improving the mechanical property of FW as compared to CW. Hence, the better performance of FW within the soil matrix was attributed to its higher AUL as compared to CW.

4.3.4) Combined influence of fertilizers and WAPs on SWCC of soil

Figures 4.4 and 4.5 show the combined effect of WAP and fertilizers on SWCC of two different soils (silt loam and silt). It can be observed that the various combinations of fertilizer do not inhibit the performance of the WAPs in terms of the SWCC of the amended soils. There is an improvement in the water retention of WAP amended soils by incorporating inorganic and organic fertilizers. The improvement in water retention with WAP and fertilizers is due to the progressive reduction of soil pore volume and pore channels. To prove this point, the pore characteristics [as visualized using field emission scanning electron microscope (FESEM) images] of silt loam and silt with different combinations of WAP and fertilizers are compared in **Figure 4.6 and 4.7** respectively. As it can be observed, the pore channels and voids are filled with the incorporation of WAPs, leading to a more denser pore structure. Further densification in the soil pores can be noticed with the addition of fertilizers and the WAPs, resulting in water retention improvement.

The order of water retention behavior in both the soils for FW is as follows: bare soil (T0) < soil + FW (T8) < soil + FW+ organic (T9) < soil + FW + organic + urea (T10) < soil + FW + organic + DAP (T11) < soil + FW + organic + urea + DAP (T12). However, some decrement was found in the water retention behavior of CW amended silt loam with DAP inclusion. The order of water retention behavior in silt loam for CW is as follows: bare soil (T0) < soil + CW (T3) <soil + CW + organic + urea (T4) < soil + CW + organic + urea + DAP (T7) < soil + CW + organic+ DAP (T6) < soil + CW + organic + urea (T5). This is due to the higher sensitivity of CW to the ionic nature of the surrounding clay particles and DAP fertilizers. The reduction in water retention with the DAP addition is not observed for CW amended silty soil (BS) because of the lower clay percentage (clay content <10%). As discussed below, the measured SWCCs with different treatments are further used to compare saturated water content, FC, PWP of fertilizer, and WAP amended soils.

Figure 4.8 represents the variation in saturated water content (θ_s) of soil amended with different combinations of fertilizers and WAPs. The improvement in saturated water

T0: Bare Soil; T2: Soil + Organic + DAP; T3: Soil + CW; T8: Soil + FW;

T7: Soil + CW + Organic + Urea + DAP; T12: Soil + FW + Organic + Urea + DAP

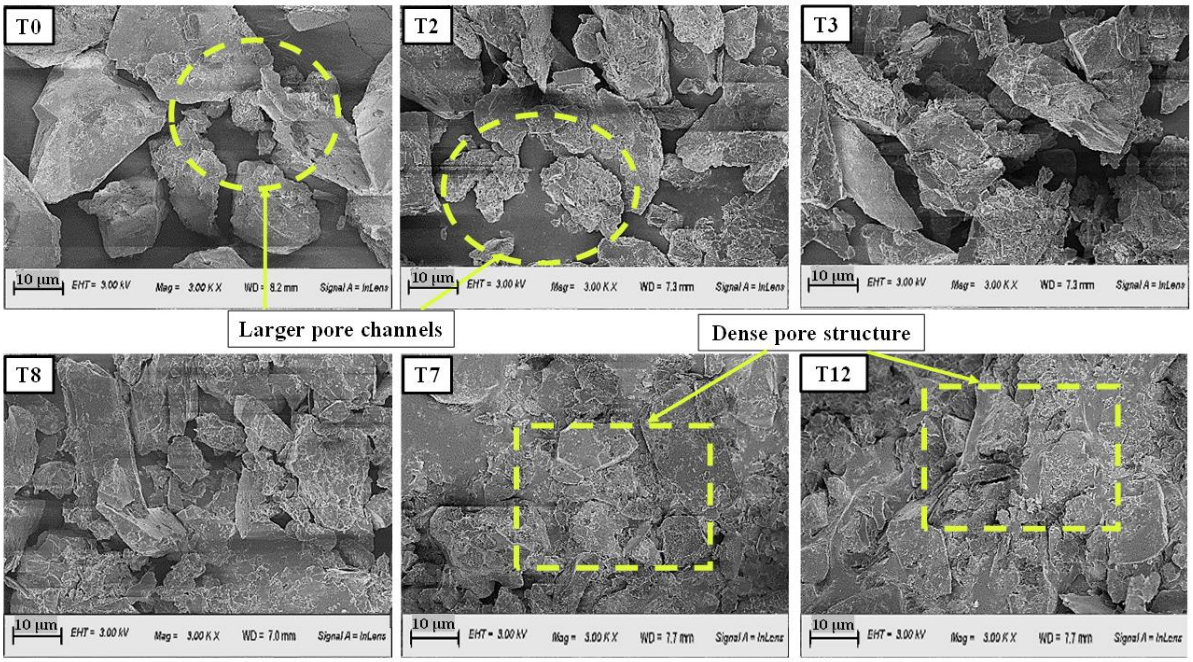


Figure 4.6. Soil-pore characteristics (as visualized using FESEM) of water-absorbing polymer and fertilizer treated Silt loam at 3000X magnification

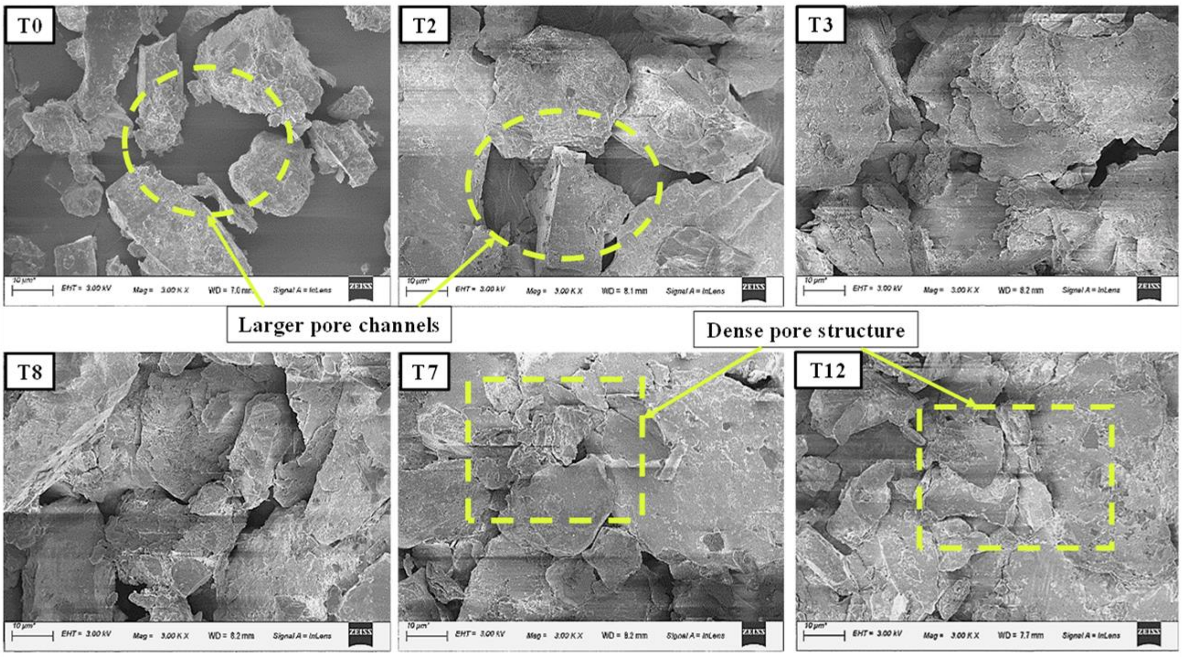
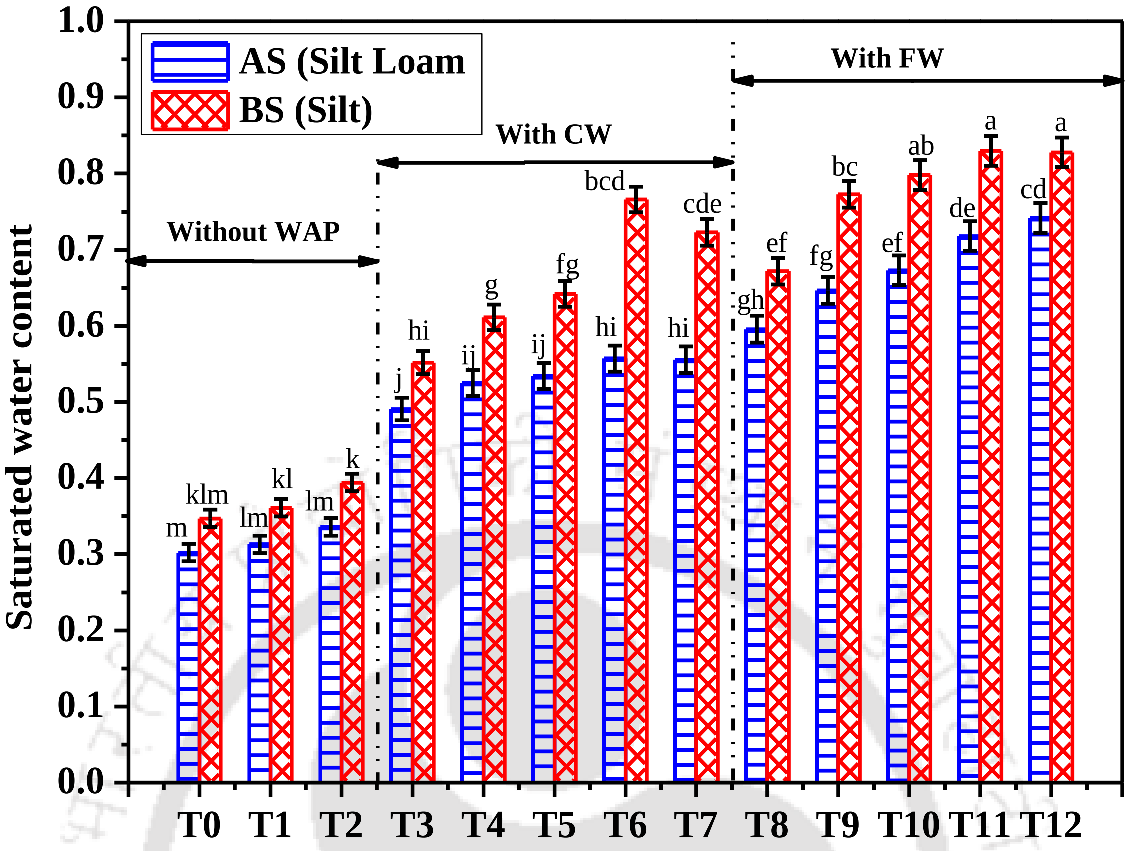


Figure 4.7. Soil-pore characteristics (as visualized using FESEM) of water-absorbing polymer and fertilizer treated Silt at 3000X magnification

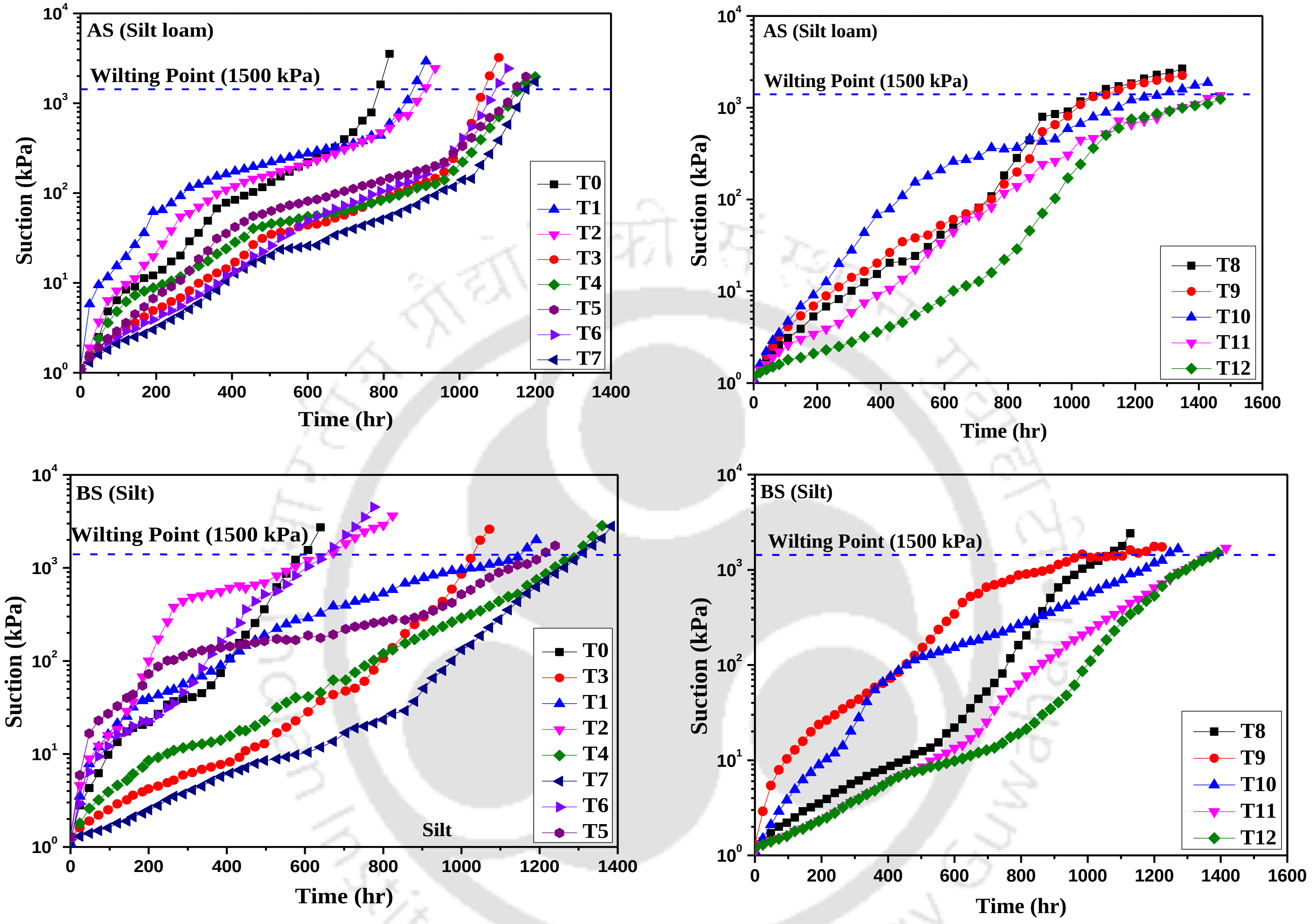


T0: Bare Soil; T1: Soil + Organic + Urea; T2: Soil + Organic + DAP; T3: Soil + CW; T4: Soil + CW + Organic; T5: Soil + CW + Organic + Urea: T6: Soil + CW + Organic + DAP; T7: Soil + CW + Organic + Urea + DAP, T8: Soil + FW; T9: Soil + FW + Organic; T10: Soil + FW + Organic + Urea; T11: Soil + FW + Organic + DAP; T12: Soil + FW + Organic + Urea + DAP

Figure 4.8. Effect of different WAP and fertilizer treatments on saturated water content of the used soils. [Note: Different letter indicates a significant difference (at $p \leq 0.05$)]

content θ_s is more in silty soil than silt loam. This is directly related to the presence of higher clay content in silt loam that restricts the swelling of WAP. Comparing both the WAPs, the performance of FW was found to be higher than CW for improving the θ_s value of soil. For FW, the increasing order of saturated water content is found to be similar to the order of water retention behavior (i.e., T8< T9< T10< T11< T12< T13) for both the soils.

The results of **Figure 4.8** clearly show that fertilizers application does not have negative impact on the saturated water content of WAP amended soils, which helps to improve the soil-water storage capacity of soils under water stress conditions. Even though there is a



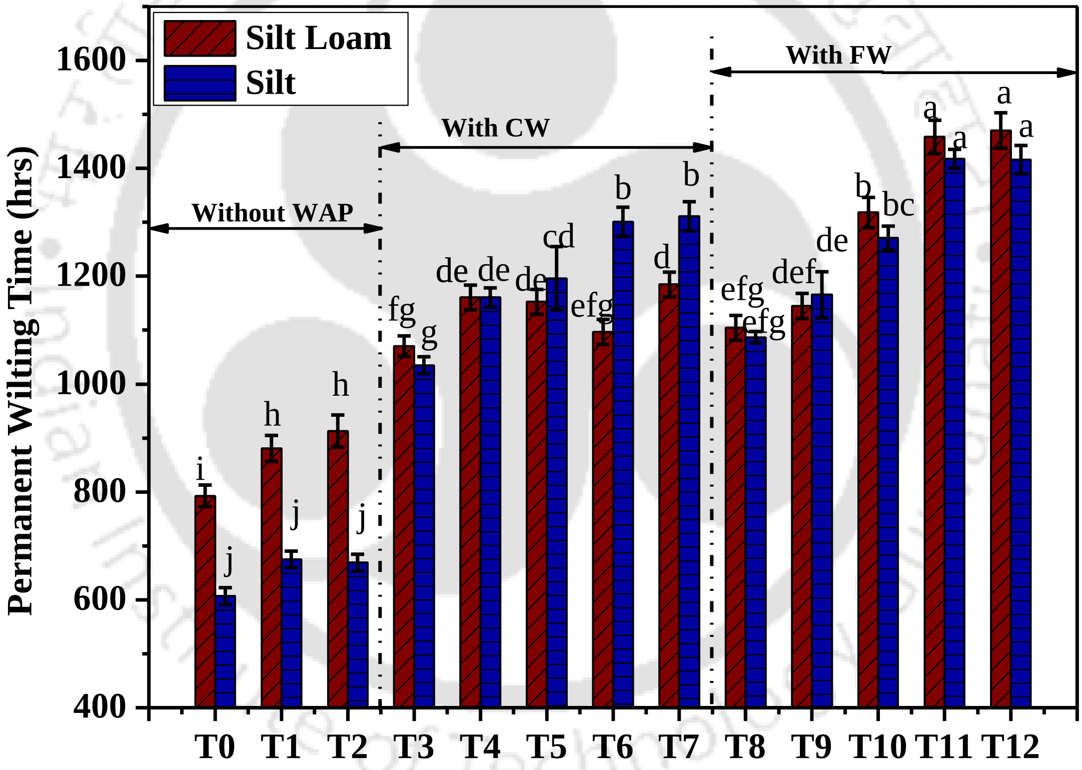
T0: Bare Soil; T1: Soil + Organic + Urea; T2: Soil + Organic + DAP; T3: Soil + CW; T4: Soil + CW + Organic; T5: Soil + CW + Organic + Urea: T6: Soil + CW + Organic + DAP; T7: Soil + CW+ Organic + Urea + DAP; T8: Soil + FW; T9: Soil + FW + Organic; T10: Soil + FW + Organic + Urea; T11: Soil + FW+ Organic + DAP; T12: Soil + FW + Organic + Urea + DAP

Figure 4.9. Variation of suction at different time intervals with different treatments for the used soils

reduction of water absorbency of WAPs in the presence of fertilizer, the water retention behavior is still enhanced.

4.3.5) Effect of different WAP and fertilizer treatments on wilting time

Figure 4.9 represents the continuous drying curves (matric suction versus time) for both soils at different fertilizer combinations with the amendment of CW and FW. Generally, the time required to reach PWP is denoted as the permanent wilting time (or plant survival time) under water stress conditions, since plant roots cannot extract water beyond this point (Abedi-Koupai et al., 2008). Therefore, the time to reach the suction value of 1500 kPa was calculated. The obtained values of permanent wilting time for different combinations of fertilizers and WAP amended soils are presented in **Figure 4.10**. The Figure shows that the addition of fertilizers alone significantly affects the wilting time in silt loam soil, whereas,



T0: Bare Soil; T1: Soil + Organic + Urea; T2: Soil + Organic + DAP; T3: Soil + CW; T4: Soil + CW + Organic; T5: Soil + CW + Organic + Urea: T6: Soil + CW + Organic + DAP; T7: Soil + CW + Organic + Urea + DAP, T8: Soil + FW; T9: Soil + FW + Organic; T10: Soil + FW + Organic + Urea; T11: Soil + FW + Organic + DAP; T12: Soil + FW + Organic + Urea + DAP

Figure 4.10. Effect of different water-absorbing polymer (WAP) and fertilizer treatments on permanent wilting time [Note: Different letter indicates a significant difference (at $p < 0.05$)]

for silty soil, the influence is not significant. The wilting time has been significantly increased due to the addition of WAPs for both soils. For silty soil, the wilting time was increased by 1.7 times and 1.8 times with the addition of CW and FW, respectively. Similarly, the wilting time increased by 1.3 times and 1.4 times in CW and FW amended silt loam soil. The combined application of WAP inorganic and organic fertilizers (T5, T6, T7, T10, T11, T12) have significantly increased the wilting time compared to only WAP (T3 and T8). The plant wilting time was increased by 1.9 times and 2.3 times as compared to bare soil in silt loam and silty soil, respectively, with FW and fertilizers (T12). However, the increment in wilting time is found to be less in CW amended silt loam soil due to the sensitivity of CW in the presence of clay particles. For both the soils, T7 (using CW) and T12 (using FW) combinations gave the best results in terms of wilting time. These results suggest that combined application of WAP and fertilizers can sustain water availability in the soil for extended duration than control soil under water stress conditions. This would help to reduce irrigation frequency and facilitate better plant growth.

4.3.6) Effect of WAPs and fertilizers on plant available water content

Plant available water content (PAWC) is one of the essential parameters from the agriculture point of view. It quantifies the amount of water held by soil, and available for plant growth/ development. It is defined as the arithmetic difference between field capacity (FC) and permanent wilting point (PWP). The quantification of FC in laboratory conditions is complex, and therefore volumetric water content corresponding to the matric suction value of 33 kPa is considered as FC (Colman 1947). On the other hand, the volumetric water content corresponding to the suction value of 1500 kPa is known as PWP (Hillel, 1971). After the suction value exceeds 1500 kPa, the stored water in the soil is retained in smaller soil-pores (less than 0.2 μm to 0.5 μm), from where roots cannot extract water and plants undergo wilting (Narajry et al., 2012).

Figure 4.11 and Table 4.2 shows the influence of different combinations of WAPs and fertilizers on FC, PWP, and PAWC for both soils. It can be observed that the addition of organic and inorganic fertilizers has the minimum effect on the water availability to plants because fertilizer addition increases both FC and PWP of soil. A significant improvement (p-value <0.05) in PAWC was noticed in WAP amended soils (both silt loam and silt) with the addition of CW and FW. **Table 4.2** further indicates that the soil texture significantly influences the PAWC of bare soil and WAP-fertilizer-treated soils. The PAWC is improved by 1.9 times and 1.5 times with CW addition in silt loam and silt, respectively. Similarly, the addition of FW has increased the PAWC of silt loam and silt by 2.2 times and 1.9 times, respectively. The combined use of fertilizer and FW have increased the PAWC, FC, and PWP of soil. Silty soil has more improvement in PAWC than the silt loam for all the treatments. The PAWC is increased with the different fertilizer treatments for FW amended soils. In contrast, for CW, T4 and T5 (which are exclusive of DAP fertilizer) gave the best results in terms of PAWC for both silt loam and silt. It is visible the from Figure that the use of DAP along with CW (T6 and T7) has significantly increased the PWP (close to 25%). A marginal increase in the field capacity was also observed. Due to this, PAWC has slightly decreased compared to other treatments, suggesting less stored water is available to plants. However, the overall increment in PAWC for these treatments (T6 and T7) is not significantly different than the CW amended

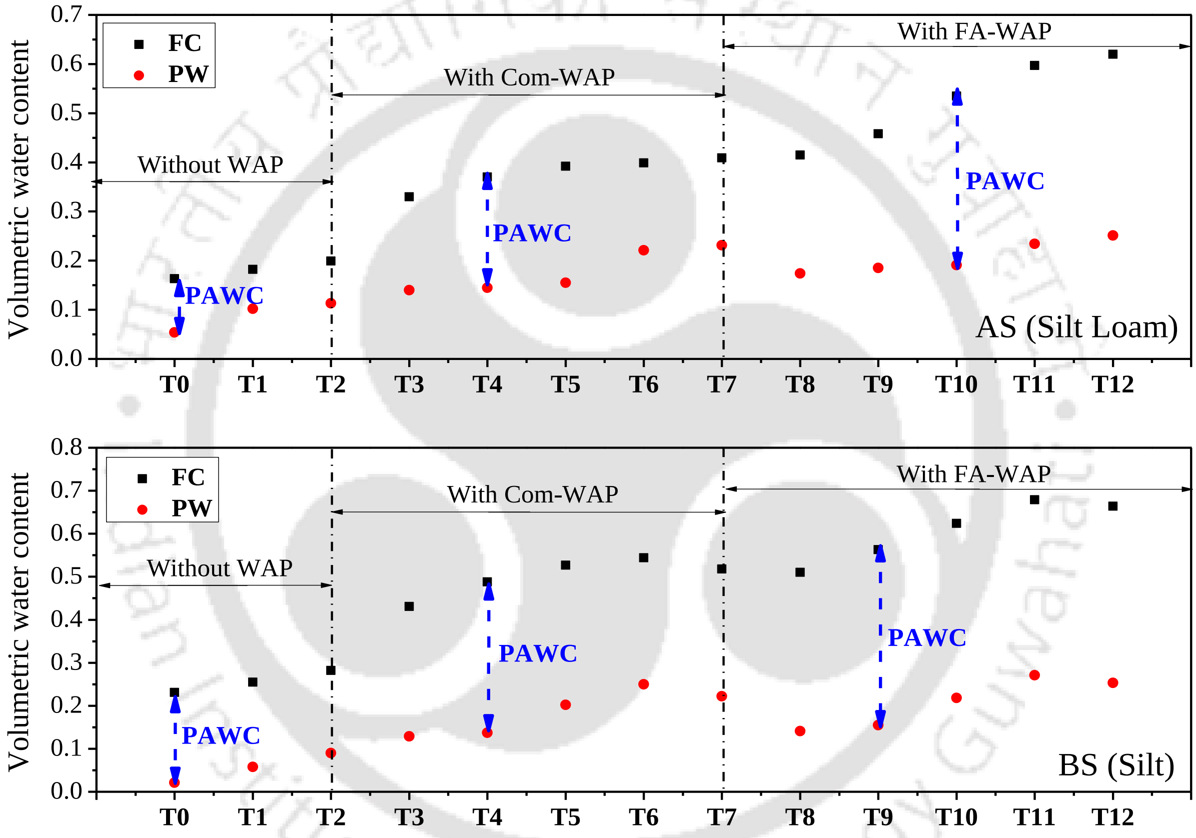
Table 4.2. Effect of different water-absorbing polymer (WAP) and fertilizer treatments on plant available water content (PAWC) of the used soils

Treatments	**Agricultural Soil** (mean value)	**Brahmaputra silt** (mean value)
T0	0.109^{l}	0.21^{ij}
T1	0.08^{m}	0.197^{jk}
T2	0.086^{lm}	0.192^{jk}
T3	0.19^{jk}	0.302^{ef}
T4	0.225^{hi}	0.351^{bcd}
T5	0.237^{h}	0.326^{de}
T6	0.178^{k}	0.295^{fg}
T7	0.178^{k}	0.297^{fg}
T8	0.241^{h}	0.369^{b}
T9	0.272^{g}	0.408^{a}
T10	0.343^{cd}	0.406^{a}
T11	0.362^{bc}	0.408^{a}
T12	0.368^{bc}	0.411^{a}

Note: The similar superscript letters indicates that the treatments are not statistically different soils (T3). These observations indicate that the fertilizer addition along with WAP has no significant negative influence on SWCC of soil and other allied parameters (FC, PAWC, survival time). Hence, WAPs can be confidently added to the agricultural field to increase plant growth and survival under water stress conditions in the presence of organic and inorganic fertilizers considered in this study.

4.4) Conclusions

The present study evaluated the influence of different organic (cow manure) and inorganic fertilizer (urea and DAP) application on the water absorbency and water retention characteristics of water-absorbing polymer (WAP) amended soils. The water absorbency of two different WAPs (a commercial WAP (CW) and in-house synthesized fly ash WAP (FW))



T0: Bare Soil; T1: Soil + Organic + Urea; T2: Soil + Organic + DAP; T3: Soil + Com-WAP T4: Soil + Com-WAP + Organic; T5: Soil + Com-WAP + Organic + Urea: T6: Soil + Com -WAP + Organic + DAP; T7: Soil + Com-WAP + Organic + Urea + DAP,;T8: Soil + FA-WAP; T9: Soil + FA-WAP + Organic; T10: Soil + FA-WAP + Organic + Urea; T11: Soil + FA-WAP + Organic + DAP; T12: Soil + FA-WAP + Organic + Urea + DAP

Figure 4.11. Effect of different WAP and fertilizer treatments on FC, PWP, and PAWC for the used soils

was evaluated in the presence of varying concentrations of fertilizers. The soil-water characteristics curve (SWCC) of two textured soils (silt loam and silt) was measured with 13 combinations of WAPs and fertilizers. A statistical significance test was conducted to analyze the effect of fertilizer type and concentrations on water absorbency of WAP and SWCC of WAP amended soils. The following important points are drawn from this objective:

a) The water absorbency of both WAPs was decreased with the increasing fertilizer concentrations. The reduction in water absorbency of WAP was marginal for non-ionic urea fertilizer, whereas the ionic DAP fertilizer significantly reduced (p-value <0.05) the water absorbency.

b) The sensitivity of FW to ionic fertilizer was less than CW due to its presence of support materials (i.e., fly ash) onto the polymer network of WAP.

c) The addition of fertilizer has improved the SWCC of both the soil at the higher suction range. The improvement in SWCC was more in the presence of DAP as compared to urea due to the higher solubility and mobility of urea.

d) The incorporation of both WAPs has significantly improved the SWCC of both soils. The improvement is higher in silty soil as compared to silt loam due to the presence of higher clay particles in the latter.

e) The SWCC of WAP and fertilizers amended soil showed that there is no negative influence of fertilizers on the performance of WAP. The SWCC is improved with the inclusion of fertilizers along with WAPs in all the combinations.

f) The increase in saturated water content is more for FW amended soils as compared to the CW amended soils.

g) The combined addition of FW and fertilizers has further increased the plant wilting time by 1.9 times and 2.3 times compared to bare soil in silt loam (AS) and silty soil (BS), respectively.

h) The improvement in plant available water content (PAWC) of fertilizer and WAP amended soils indicate higher water availability to plant roots.

The above conclusions indicate that the water retention characteristics of WAP amended soil are not compromised in the presence of organic and inorganic fertilizers. This conclusion is despite the fact that the overall water absorbency of WAPs is reduced in the presence of fertilizers.

Chapter 5

Laboratory and field evaluation of vegetation growth in unsaturated soil amended with WAP

5.1) Introduction

In 2023, the population would have surpassed 8 billion, making feeding a burgeoning population a challenging task. Overpopulation has raised the strain on agriculture in terms of food security. The agricultural sector plays an important role in economic development, and its productivity is affected by a range of elements such as soil, water, plant variety, climatic/environmental conditions, etc. (Loomis et al., 1971). Recently, the adaptation of modified plant varieties, synthetic fertilizers, and agricultural technology has been primarily focused on increasing agricultural production (Gardner, 2009). In the current century, human-caused changes in numerous elements such as climate change and increases the global temperature due to several activities. It causes an increase in the water crisis for both domestic and agricultural needs that limits agricultural productivity (Le Houérou, 1996). Water stress also impacts bioengineering, green infrastructure, and dry environments (Sekharan et al., 2019). Water stress has a wide range of detrimental effects on plant growth, survival, and yield (Altieri, 2009). Therefore, it is important to understand how plants are subjected to water stress, how plants endure diverse environmental boundary conditions, and at what instance plants start experiencing water stress.

The status of water availability in the soil matrix can be quantified using the unsaturated soil-water characteristic curve (SWCC). The SWCC is useful for determining irrigation scheduling, frequency, and permanent wilting point (PWP). It is well known, PWP directly depends on the root's ability to extract the water from the soil medium and varies with soil type and plant species. Previous studies determined PWP from SWCC as the water content corresponding to a suction value of 1500 kPa, irrespective of plant species and soil textures (Garg et al., 2017; Zhang and Han, 2019). This reference value is often used for modelling water transfer in the soil-plant-atmosphere continuum in crop growth models (Richards and Fireman, 1943). The recent literature (Garg et al., 2020; Bordoloi et al., 2022) indicates that PWP at 1500 kPa might not be a correct procedure for defining plant water extraction and can lead to under-irrigation (earlier stage wilt) and over-irrigation (excess water loss). Furthermore, the same literature determined the precise PWP that is linked with plant physiological parameters, especially for non-crop species, such as

Axonopus compressus and *Eichhornia crassipes*. Plant physiological factors such as stomatal conductance (SC) and photosynthetic yield (PY) is affected by leaf water potential and water availability in the root zone during water stress (Choat et al., 2018). It is obvious that these constraints (SWCC, SC, PY) are an efficient technique to identify ongoing water stress that causes temporary or permanent plant damage (Han et al., 2013).

Most of the previous literature focused on the effects of water stress (drought stress) on plant growth and crop yield (Anjum et al., 2017). Water stress investigates by focusing on a single indication, either soil or plant. Important soil indicators such as SWCC, soil suction, plant available water content and permanent wilting point are considered (Da Silva et al., 2014). Plant indicators for investigating water stress, such as physiological parameters (stomatal conductance, photosynthetic yield), phenotypical parameters (plant height, canopy area) and biochemical analyses are considered (Zhang et al., 2022). However, the combined interaction of soil and plant elements has been not explored in detail in the previous literature. Therefore, the motivation of this study is to investigate the state of water stress in relation to soil suction and physiological plant parameters (SC and PY). This study focuses on the uniqueness and how wilting and physiological characteristics of plants change/behave in conjunction of bare and amended soil under water stress.

The primary objective of this chapter is 1) unravelling the progression of drought stress in plants by relating soil suction and plant physiological indicators in lab condition for bean and radish, 2) to establish the wilting pattern by linking soil suction with plant physiological parameters in field condition for radish and bean 3) to study the impact of a novel fly ash water-absorbing polymer (FW) soil retention behavior and plant yield to tackle water deficit condition in tomato species.

5.2) Materials and methodology

5.2.1) Site description

The study was carried out in a laboratory and field condition on the IIT Guwahati campus, which is located in Assam province of India (26°11'05.6"N 91°41'33.2"E). For laboratory condition, the greenhouse structure is comprised of translucent plastic fiber material sheets on the sides and top, which help to maintain environment condition while allowing natural sunlight to enter. In addition, artificial lighting was constructed to provide optimal growing conditions for the plants. The experiment was carried out at a regulated temperature of 25-28°C with a humidity of 50%. Beans (Phaseolus vulgaris), radish (Raphanus sativus) and tomato (Solanum lycopersicum), were selected from distinct families (Beans-Legumes, Radish-Brassicaceae, Tomato- Solanaceae) to assess characteristics of plant physiological indicators. These species were chosen based on consumption (ideal for domestic use) and higher source of vitamins and nutrients (Ebert, 2012).

5.2.2) Soil Properties and WAPs

In this study, two different soil types were collected from an agricultural field and sieved using a 4.75mm sieve to remove the plastic and other debris. The soils were classed as silt loam and silt according to USDA classification guidelines. The two distinct water-absorbing polymers (WAPs) were used: 1) a low-cost water-absorbing polymer produced from fly ash developed in-house (FW) (Saha et al., 2020d) and another commercially available water-absorbing polymer (CW) obtained from the Aura limited firm in India. The detailed classification and WAP characterization were discussed in chapter 3

5.2.3) Measurements of soil and plant parameters

5.2.3.1) SWCC and its parameters

To establish the soil-water retention curve (SWCC) and its parameters, soil suction and water content sensors were installed and around 5cm away from the plant's root zone. During an water stress condition, the SWCC was established by continuously measuring soil suction and volumetric water content with the TERROS 21 and 5 TM sensors, respectively. The adopted methodology and details of used sensor were presented in **chapter 3 and 4**. Van Genuchten (1980) is utilized for fitting the SWCC from experimental data to quantify the SWCC parameters. In this model, the following equations are used:

$$\theta_{\psi} = \theta_r + \frac{(\theta_s - \theta_r)}{\left[\left\{1 + (\psi a_{vg})^{n_{vg}}\right\}^{m_{vg}}\right]} \quad \text{Eq.5.1}$$

$$m_{vg} = 1 - \frac{1}{n_{vg}} \quad \text{Eq.5.2}$$

Where θ_{ψ} = soil water content at any matric suction, a_{vg} = related to the air entry value, n_{vg} = rate of water extraction, m_{vg} = parameter related to the residual water content, θ_s = saturated water content, θ_r = residual water content, and ψ = soil matric suction.

The important parameters evaluated from the established fitted SWCC, to know the state of water held and stored in the soil voids, and available water to the plant roots in the soil. The SWCC provides the following important parameters: saturation water content (SWC), plant available water content (PAWC), and plant survival time/plant wilting time (PWT). SWC shows the soil sample at its fully saturated state and the maximum water storage of the soil (Saxton et al., 1986). The arithmetic difference between field capacity (FC) and permanent wilting point (PWP) is plant available water content (PWAC). Field capacity is the quantity of water retained in soil pores after excessive vertical drainage, whereas the permanent wilting point is the amount of water beyond which the plant is unable to draw water from the soil (Colman, 1947). Permanent wilting time (PWT) denotes the time needed to reach the permanent wilting point during water stress conditions (Abedi-Koupai et al., 2008).

5.2.3.2) Stomatal Conductance and Photosynthetic yield

Plants generally require a constant supply of water to maintain their metabolic activities, and lack of water causes many changes in the plant, from the cellular to the phenotypic level. One of the first responses to water stress is the closure of stomata, which regulates the changes in the transpiration rate from the leaves (Pirasteh-Anosheh et al., 2016). The fluctuation of transpiration in leaves was measured as a stomatal conductance parameter (Miyashita et al., 2005). Stomatal conductance (SC) is determined by the density of stomata, the size of stomata, and the degree of stomata open pores (Eensalu, 2008). Stomatal conductance (SC) was determined using the SC-1 Leaf Porometer (METER Group, Inc., USA), a desiccant-based device that determines the SC of a leaf by measuring humidity levels between two known conductance elements in series (Farquhar and Wong, 1984).

Photosynthetic yield is another important parameter influenced by water stress and dependent on stomatal openings for gaseous exchange. Photosynthesis rate was determined using a photosynthetic yield (PY) analyzer (MINI-PAM, Heinz Walz GmbH, Effeltrich, Germany). The MINI-PAM-II measures fluorescence by detecting light that excites by saturation pulses (White and Critchley 1999). Therefore, PY is expressed as F_v/F_m, where F_v is the variable fluorescence recorded on a dark acclimated leaf adaptation and F_m is the maximum fluorescence emission observed on a dark acclimated leaf adaptation. For the dark adaptation sample, close the leaf clip for 10 minutes on the leaves and then record the PY ratio with measuring equipment. The detail of SC-1 Leaf Porometer and MINI-PAM-II instruments were presented in **Chapter 3**. The SC and PY were measured around Mid-day (around 12:00 PM (full sunlight)) when transpiration is expected to be at its peak (Monteith and Bull 1970).

5.2.4) Yield parameters

Yield is the most essential characteristic for commercial and agricultural purposes. Bean yield is measured as the parameters of fruit weight and number of fruits, whereas radish yield is measured by fruit weight and length of fruits. (Fernandez et al., 2006; Zha and Liu, 2018). Beans are typically harvested when they reach a length of 4-7 inches, whereas radishes are harvested when they reach a width of 2.5 cm. Beans were harvested twice a week, whereas radishes were harvested at the end of their life cycle. Tomato yields were harvested once in a week at the light red to red-ripe stage and measured yield parameters include the number of fruits per plot and total weight of fruits per plot (Birhanu and Tilahun, 2010). The total weight of fruits was calculated at the end of the harvest with an electronic measuring balance.

5.3) Results and Discussion

5.3.1) Laboratory results

5.3.1.1) General

To perform the experiment, 20 liters of plastic pots (25 diameter and 40 height) were chosen and number of holes were drilled (with a diameter of 6 mm) at the bottom of the pots to drain off the extra water. And filter paper is placed at the bottom of the pot to prevent soil erosion with water. WAPs and organic fertilizer were mixed together in the dry soil before filling the pots. Organic fertilizer (cow manure) is an animal waste that includes helpful microorganisms and rich in minerals and nutrients that are commonly used in agriculture. For the laboratory study, 12 different treatments (treatment numbers – 1 to 12) were selected these combinations of WAP, organic fertilizer, well water, and water stress condition. **Table 5.1** shows the detailed treatments of WAP-amended soil in different conditions. Initially, seeds were grown in a germination chamber, which provides an ideal atmosphere for better growth. The plants were transferred into pots after germination. And plants were allowed to grow to the vegetative stage (near flowering or mature stage) in a well-watered condition. The growth period of tomato species was around 90 days, whereas beans and radish took 60 days to grow. After reaching the flowering stage, certain treatments were treated for water stress, while the remaining treatments were grown in well-watered conditions. Water stress was continued until the plant reached its permanent wilting point (PWP) (near plant death). For laboratory conditions, considering two soil textures, two WAPs and two repetitions per combination, resulted in 96 different experimental pots. In each pot, the growth of two plants were monitored resulting in a total of 192 plant measurements. Considering only water-deficit drought imposition (Table 5.1), there is a total of 48 pots and 96 plant measurements.

5.3.1.2) SWCC affected by WAP, organic fertilizer and crops

The presence of WAP and crops (beans and radish) have influence on the SWCC. The variation in drying SWCC of silt and silt loam due to the addition of CW/ FW and the presence of beans crop is depicted in **Figure 5.1**. The suction and volumetric water content were continuously monitored from the vegetative stage to the wilting stage. The addition of WAP and organic fertilizer improved the water retention characteristics compared to control soil. The changes observed in SWCC can be predominantly attributed to the increase in water storage in the soil matrix due to WAP and presence of organic matter (Libohova et al., 2018; Jabro and Stevens, 2022). The reasons for the improvement in SWCC is discussed in Chapter 4 and not repeated here for brevity. **Table 5.2** lists the

Table 5.1: Details of different treatments of water-absorbing polymer (WAP) amended soil on species

Sr. No.	Description				Experiment conducted				
	WAP	**O**	**Condition**	**Symbolic represents**	**Beans (Lab)**	**Beans (Field)**	**Radish (lab)**	**Radish (field)**	**Tomato (field)**
1	No WAP	-	Well-watered	CS WW	√	–	√	–	–
2	Commercial WAP	-	Well-watered	CW WW	√	–	√	–	–
3	Fly ash-based WAP	-	Well-watered	FW WW	√	–	√	–	–
4	No WAP	√	Well-watered	CSO WW	√	√	√	√	–
5	Commercial WAP	√	Well-watered	CWO WW	√	√	√	√	–
6	Fly ash-based WAP	√	Well-watered	FWO WW	√	√	√	√	–
7	No WAP	-	Water-deficit	CS WD	√	–	√	–	–
8	Commercial WAP	-	Water-deficit	CW WD	√	–	√	–	–
9	Fly ash-based WAP	-	Water-deficit	FW WD	√	–	√	–	–
10	No WAP	√	Water-deficit	CSO WD	√	√	√	√	√
11	Commercial WAP	√	Water-deficit	CWO WD	√	√	√	√	√
12	Fly ash-based WAP	√	Water-deficit	FWO WD	√	√	√	√	√

Note: “O” used for Organic fertilizer

SWCC parameters and plant survival time for different combinations listed in **Table 5.1**. The results shows that the presence of WAPs and organic fertilizer increased the SWC, PAWC, and PWT in both silt and silt loam soil under drought condition. Previous studies, Saha et al., 2020a and Taban and Movahedi, 2006 reported an increase in SWCC parameters when the soil was amended with WAP and Organic fertilizer, respectively.

For both plant species grown in both the soils, the increasing order of SWC, PAWC, and PWT was consistently in the order: CS_WD < CSO_WD < CW_WD < CWO_WD <

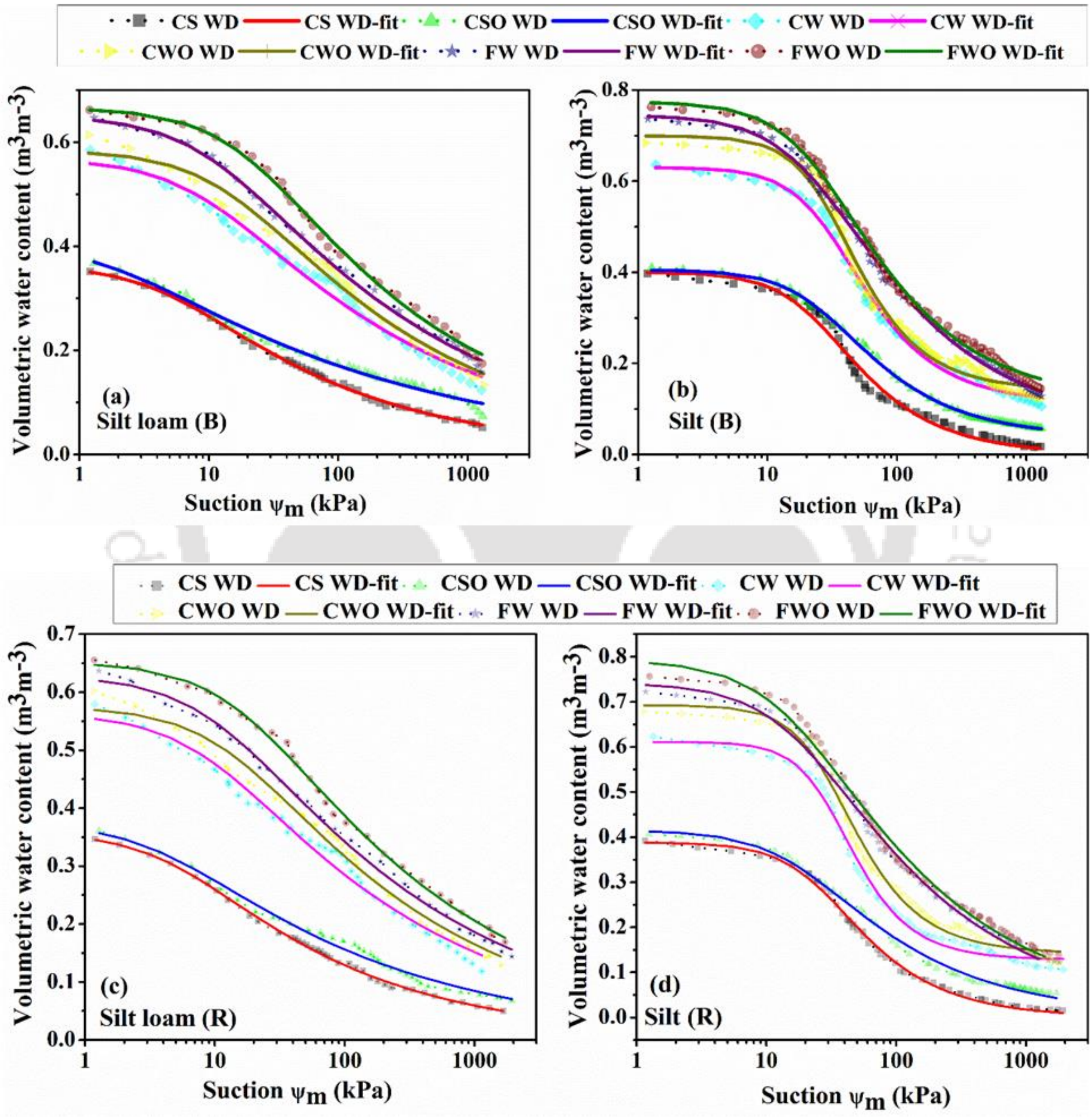


Figure 5.1: Influence of different water-absorbing polymers on SWCC of silt loam and silt on beans.

Table 5.2 The SWCC parameters and survival time of beans and radish in silt loam and silt

Treatments	CS WD	CSO WD	CW WD	CWO WD	FW WD	FWO WD
			Beans grown in Silt loam			
θ_s	0.363	0.404	0.568	0.584	0.651	0.666
α_{vg}	1.973	1.576	1.066	0.679	0.682	0.483
n_{vg}	1.134	1.217	1.271	1.294	1.271	1.324
R^2	0.998	0.989	0.983	0.984	0.997	0.995
PAWC	0.134	0.137	0.268	0.276	0.298	0.357
PWT (hrs)	630	690	840	872	912	950
			Beans grown in Silt			
θ_s	0.400	0.405	0.630	0.700	0.745	0.774
α_{vg}	0.483	0.456	0.417	0.323	0.431	0.389
n_{vg}	1.657	1.755	1.975	2.148	1.871	1.992
R^2	0.986	0.998	0.994	0.987	0.997	0.996
PAWC	0.246	0.243	0.374	0.405	0.412	0.417
PWT (hrs)	436	461	695	732	743	777
			Radish grown in Silt loam			
θ_s	0.345	0.360	0.585	0.607	0.635	0.658
α_{vg}	1.987	1.596	1.266	0.689	0.696	0.493
n_{vg}	1.104	1.208	1.257	1.286	1.264	1.319
R^2	0.993	0.991	0.987	0.994	0.987	0.991
PAWC	0.133	0.135	0.262	0.281	0.285	0.322
PWT (hrs)	600	638	864	900	936	965
			Radish grown in Silt			
θ_s	0.392	0.406	0.623	0.653	0.722	0.756
α_{vg}	0.490	0.462	0.424	0.331	0.436	0.395
n_{vg}	1.607	1.723	1.971	2.113	1.882	1.989
R^2	0.989	0.993	0.997	0.991	0.987	0.997
PAWC	0.237	0.242	0.347	0.38	0.403	0.405
PWT (hrs)	456	499	696	732	768	806

Note: θ_s -Saturation water content, α_{vg} = related to the air entry value, n_{vg} = rate of water extraction, PAWC- plant available water content, PWT- permanent wilting time.

FW_WD < FWO_WD. The highest SWC value measured was 0.774 in silt with beans species, which is an overall contribution of WAP, organic fertilizer and root conFigureuration. In the presence of WAP, the PAWC improvement is approximately 2 times in silt loam, and 1.5 times in silt for both the species. The PWT was improved by 1.35 times for CW and 1.5 times for FW in both the species grown in silt loam, whereas 1.5 times for CW and 1.7 times for FW for both the species in silt. These results were similar to the trends observed in the literature without considering the plant species (Saha et al., 2020a). It is explicit that the presence of WAP and organic fertilizer increased the water retention and PWT under drought condition for both plant species grown in silt loam and silt.

5.3.1.3) Plant parameters for different combinations

5.3.1.3.1) Plant physiological attributes

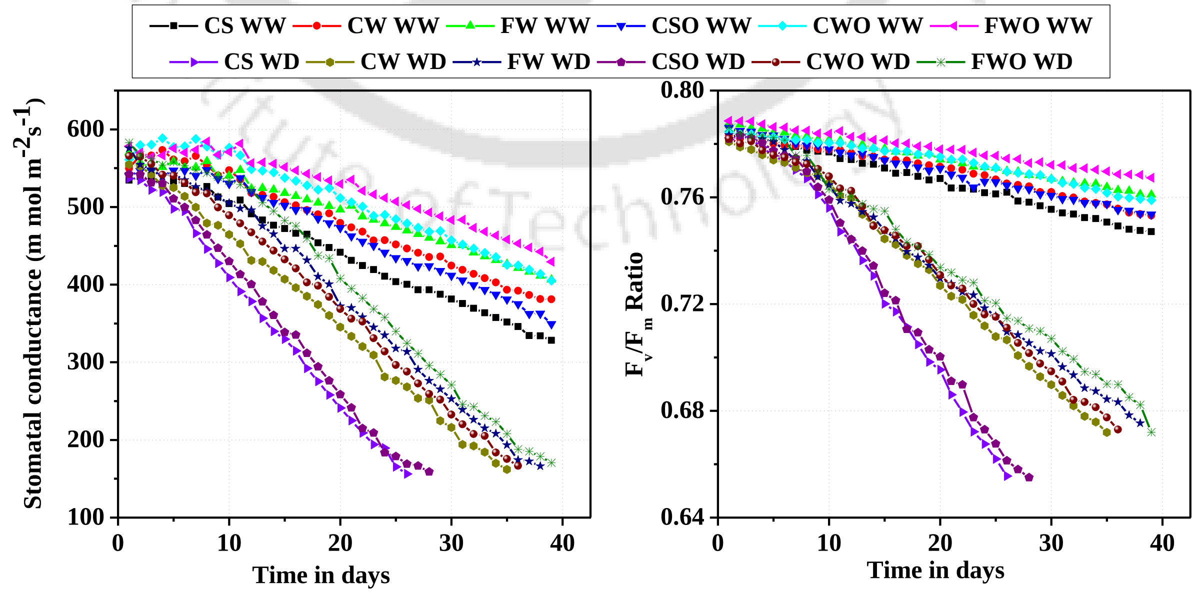
The maximum SC and PY values were measured in full sunlight (12:00 PM) to assess the impact of drought condition on plant physiology under WAP and organic fertilizer amended soil. For the sake of convenience, the term "maximum" SC and PY is not used in subsequent discussions. The SC and PY were measured as a function of time starting from well-watered condition to permanent wilting for both plant species in two soils with different amendments. The result of beans and radish grown in silt loam and silt are shown in **Figure 5.2.** Under water-deficit condition, the SC value decreases for all the combinations due to the closing of stomata in the leaves. It is understood that the stomata closure happens during restricted water availability (Chaves et al., 2016). The rate of SC decrease was quicker in the control soil, soil with OC compared to WAP amended soil. The SC at the beginning of the drought cycle (SC_b) was 534-570 m mol m^{-2} s^{-1} for beans and 377-430 m mol m^{-2} s^{-1} for radish considering all combinations in silt and silt loam. The SC at the end of drought experiment (SC_e) reduced to 131.1- 162.4 m mol m^{-2} s^{-1} for beans and 90.3- 113.9 m mol m^{-2} s^{-1} for radish.

At SC_e, the leaf was dry and SC could not be measured beyond this point. Therefore, minimum measurable SC is considered as the point of permanent wilting in plant species. According to Mullers et al., (2022), SC measurements depend on the leaf status/ health, and measurements are difficult if the leaf appears completely dry. For water-deficit condition, SC_e was 143.8 m mol m^{-2} s^{-1} for control soil whereas for WAP amendment it was 151 m mol m^{-2} s^{-1} in beans. Similarly, for radish, SC_e was 108 m mol m^{-2} s^{-1} for control soil, and for WAP amendment it was 112.7 m mol m^{-2} s^{-1}. For well-watered condition, SC_e

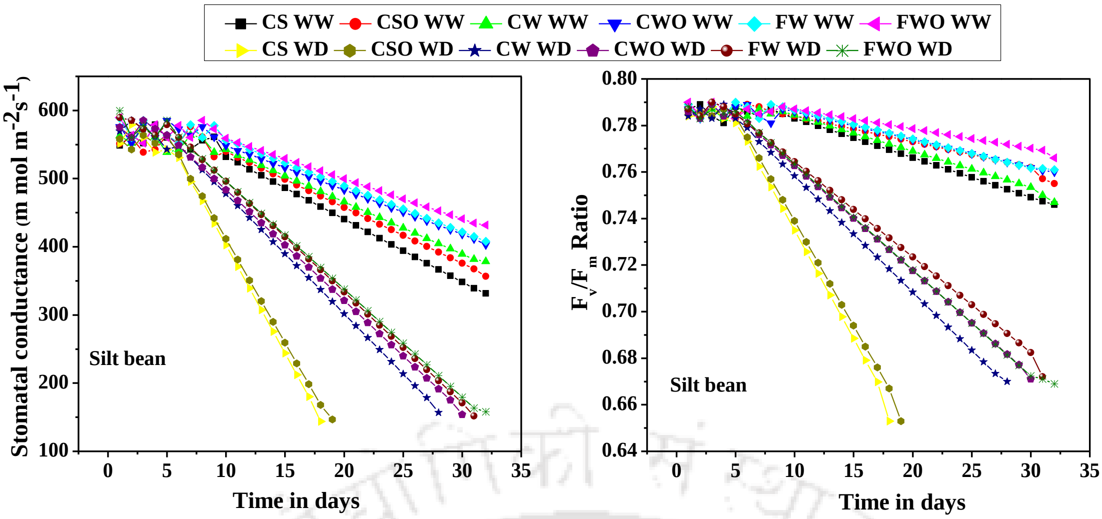
was high at 328.3 and 231.6 m mol m^{-2} s^{-1} for control soil whereas for WAP amendment it was 378 and 239.8 m mol m^{-2} s^{-1} in beans and radish, respectively. The result indicates that SC is sensitive to the type of plant species and soil amendment. The increasing order of SC values with amendment followed the sequence CS < CSO < CW < CWO < FW < FWO.

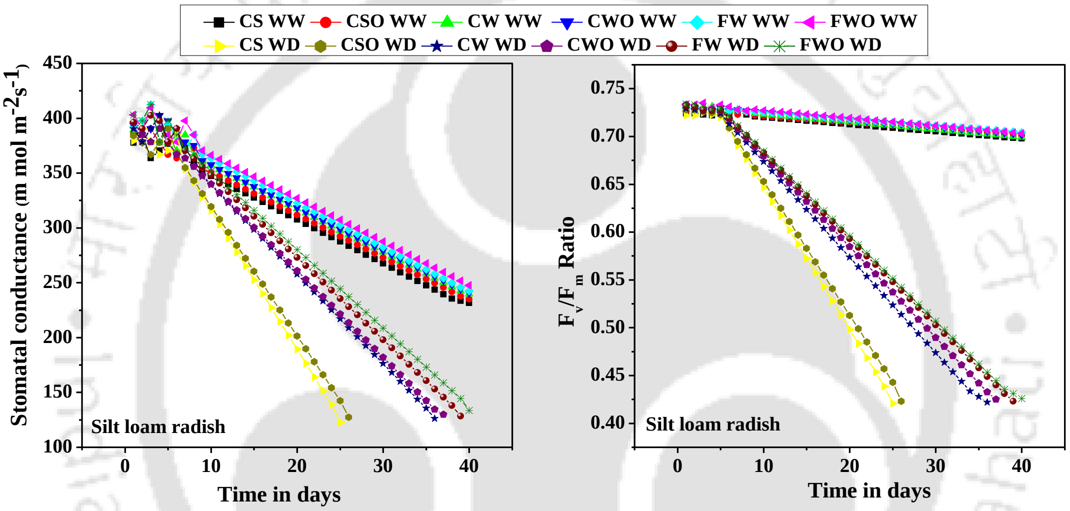
The PY represented by F_v/F_m is another important indicator for assessing drought stress in plants (Xie et al., 2021). Under well-watered condition, the PY is comparable for all combinations at the start of the experiment and falls in the range 0.782- 0.790 for beans and 0.724- 0.738 for radish. Similar to SC, the PY value decreased during the drought condition till the plant permanently wilted. Considering all the combinations, the PY value dropped from 0.757 to 0.66 for beans and 0.736 to 0.415 for radish in both silt and silt loam starting from well-watered vegetation stage to completely wilted stage. These trends were similar to previous literature where PY reduced from 0.83 to 0.6 for Jatropha Curcas L. species (Santos et al., 2013). For well-watered condition, PY at the end of experiment (PY_e) was 0.746 and 0.698 in control soil whereas for WAP amendment it was 0.747 and 0.699 in beans and radish, respectively.

For water-deficit condition, PY_e was 0.653 and 0.425 in control soil whereas for WAP amendment it was 0.67 and 0.417 in beans and radish, respectively. The increasing order of PY values with amendment was CS < CSO < CW < CWO < FW < FWO. For completeness, the initial and final SC, PY values obtained for different combinations are listed in **Table 5.3.** It is demonstrated from this section that SC and PY values are



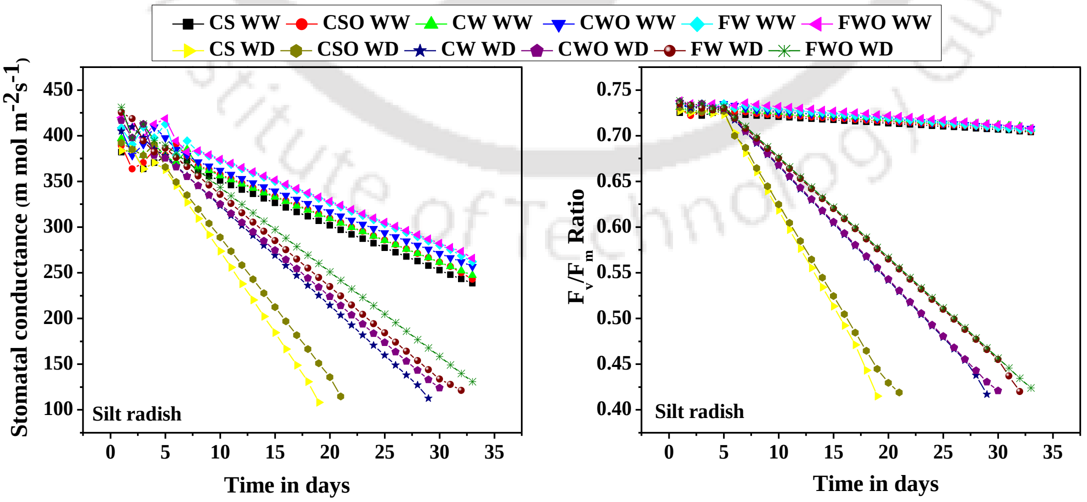
(a)





(b)

(c)



(d)

Figure 5.2: Variation of maximum SC and PY with time a) Silt loam (Beans) b) Silt (Beans) c) Silt loam (Radish) d) Silt (Radish).

Table 5.3: Summary of initial and final SC, PY values under (a) well-watered and (b) water-deficit condition

(a) Well-watered condition

	Silt loam-Beans		Silt-Beans		Silt loam-Radish		Silt-Radish	
	SC PY		SC PY		SC PY		SC PY	
CS	At 1th day	At 39th day	At 1th day	At 31th day	At 1th day	At 40th day	At 1th day	At 33th day
	534.3 0.782	328.3 0.747	548.8 0.787	331.8 0.746	377.8 .724	231.6 .698	381.8 0.725	238.5 0.704
CSO	At 1th day	At 39th day	At 1th day	At 31th day	At 1th day	At 40th day	At 1th day	At 33th day
	539.7 0.786	349.3 0.754	551.3 0.788	356.5 0.755	385.6 0.727	234.9 0.701	389.1 0.729	242.9 0.705
CW	At 1th day	At 39th day	At 1th day	At 31th day	At 1th day	At 40th day	At 1th day	At 33th day
	549.4 0.783	381.1 0.747	562.7 0.788	378.2 0.747	389.3 0.728	239.8 0.699	396.8 0.731	247.3 0.707
CWO	At 1th day	At 39th day	At 1th day	At 31th day	At 1th day	At 40th day	At 1th day	At 33th day
	561.1 0.785	405.2 0.759	576.3 0.787	403.1 0.760	393.7 0.731	240.9 0.702	406.3 0.736	256.7 0.708
FW	At 1th day	At 39th day	At 1th day	At 31th day	At 1th day	At 40th day	At 1th day	At 33th day
	570.1 0.787	406.3 0.761	588.5 0.789	407.9 0.761	392.5 0.730	242.3 0.704	408.6 0.735	262.1 0.706
FWO	At 1th day	At 39th day	At 1th day	At 31th day	At 1th day	At 40th day	At 1th day	At 33th day
	578.1 0.789	429.4 0.767	589.6 0.790	431.8 0.766	403.1 0.733	247.7 0.703	419.8 0.738	265.8 0.708

(b) Water-deficit condition

	Silt loam-Beans		Silt-Beans		Silt loam-Radish		Silt-Radish	
	SC PY		SC PY		SC PY		SC PY	
CS	At 1th day	At 26th day	At 1th day	At 18th day	At 1th day	At 25th day	At 1th day	At 19th day
	536.7 0.782	156.2 0.656	551.7 0.784	143.8 0.653	379.3 0.722	122.5 0.421	383.5 0.727	108.3 0.415
CSO	At 1th day	At 28th day	At 1th day	At 19th day	At 1th day	At 26th day	At 1th day	At 21th day
	542.2 0.782	159.1 0.655	558.2 0.785	146.6 0.653	384.1 0.728	127.5 0.423	392.3 0.731	114.8 0.419
CW	At 1th day	At 35th day	At 1th day	At 28th day	At 1th day	At 36th day	At 1th day	At 29th day
	554.5 0.781	162.1 0.672	569.6 0.784	156.8 0.67	390.3 0.729	126.1 0.422	404.8 0.734	112.7 0.417
CWO	At 1th day	At 36th day	At 1th day	At 30th day	At 1th day	At 37th day	At 1th day	At 30th day
	565.6 0.782	166.5 0.673	575.4 0.786	153.8 0.671	395.7 0.733	129.9 0.425	416.8 0.737	123.9 0.421
FW	At 1th day	At 38th day	At 1th day	At 31th day	At 1th day	At 39th day	At 1th day	At 32th day
	575.8 0.783	166.2 0.675	589.5 0.787	151.7 0.672	396.4 0.732	128.4 0.423	425.2 0.735	121.3 0.420
FWO	At 1th day	At 39th day	At 1th day	At 32th day	At 1th day	At 40th day	At 1th day	At 33th day
	582.8 0.786	170.6 0.672	599.7 0.788	158.1 0.669	402.8 0.734	133.5 0.426	430.8 0.738	130.8 0.424

influenced by the type of species, soil type, presence of organic fertilizer, and WAP treatment. It is observed from this study and from the literature that the WAP amendment has a substantial and positive impact on SC and PY values, which promotes plant health during drought stress. However, there are not many studies relating plant physiological parameters to soil suction (which indicates the water stress in soil). There are no guidelines available in the literature on how to use such a relationship for deciphering the beginning and end of water stress (drought stress) in plants under drought condition.

5.3.1.3.2) Determining the progression of drought stress in plants by relating soil suction to plant physiological attributes

The results from the previous section indicates that SC_b is influenced by plant species, soil-plant combination and soil amendment. For studying the progression of drought stress, it is felt that the measured SC should be normalized for unambiguous comparison among different measurements. This study determined normalized stomatal conductance (NSC) as the ratio of SC at any time to the maximum SC (equal to SC_b corresponding to well-watered vegetation stage before imposing drought stress). It is presumed that NSC will be better than SC for proposing generalized guidelines for determining drought stress progression in plants. It may be noted here that PY is already a ratio, and hence normalization was not done. One of the advantages of this study is the use of two different parameters, NSC and PY, for drought stress evaluation in plants. These instruments follow different working principle for studying the leaf response and hence helps to cross-verify its consistency for drought stress evaluation. The second advantage is that both NSC and PY is related to soil suction (SS), thereby correlating water stress in plants to the water stress in soil. The relationship was further used to identify the drought progression in terms of (i) drought initiation point (DIP) and (ii) final drought point (FDP) as shown in the flow diagram presented in **Figure 5.3**. The details on the determination of DIP and FDP from NSC/ PY versus SS relationship is stated below. In addition, SS corresponding to DIP and FDP (obtained from both NSC/ PY versus SS relationship) were considered as a parameter for further studying the drought stress.

The **Figure 5.4** depicts NSC/ PY versus SS relationship for beans grown in silt loam for three combinations. Only selected combinations were shown because the main aim of **Figure 5.4** is to depict the determination of DIP and FDP. The trends were similar for all the combinations considered in this study and not presented here for brevity. The measurements shown in **Figure 5.4** started one day after the irrigation was stopped for imposing drought stress in plants. No irrigation was provided further, till the complete wilting of the plants. The reviewed literature indicates that there are no guidelines for determining the point where the plant first start experiencing water stress when it is subjected to drought. Such a point is defined as DIP in this study. It is also equally important to identify the point where the plant has wilted and cannot be revived through further watering. According to this study, this point is FDP.

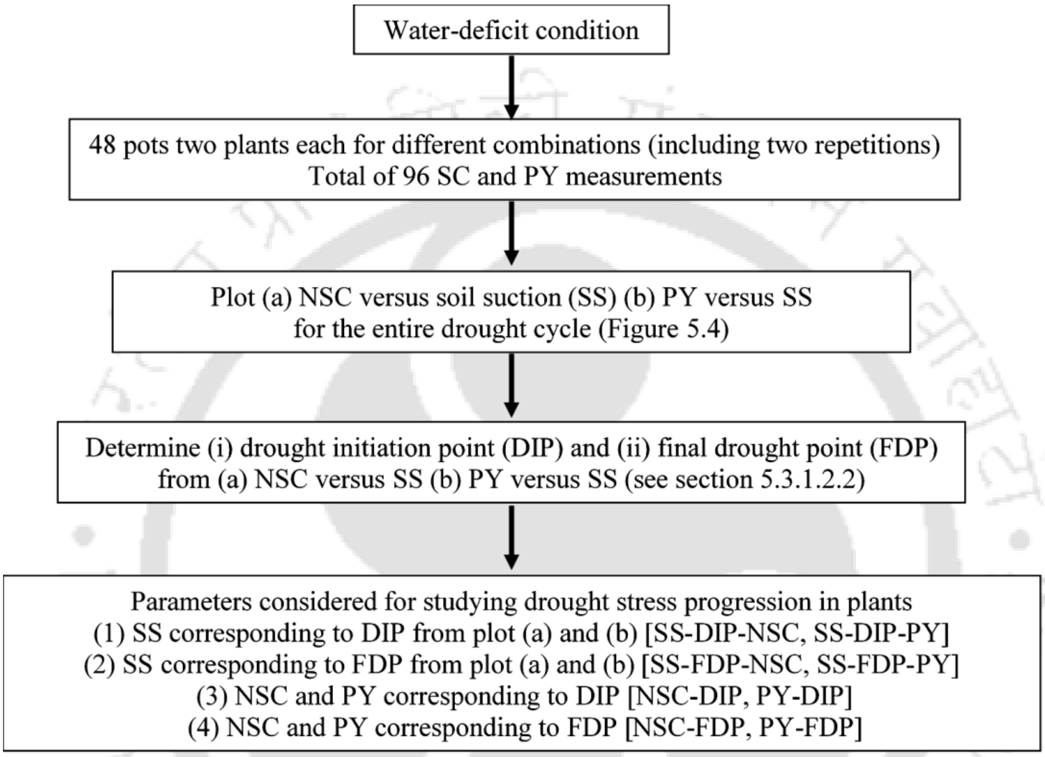
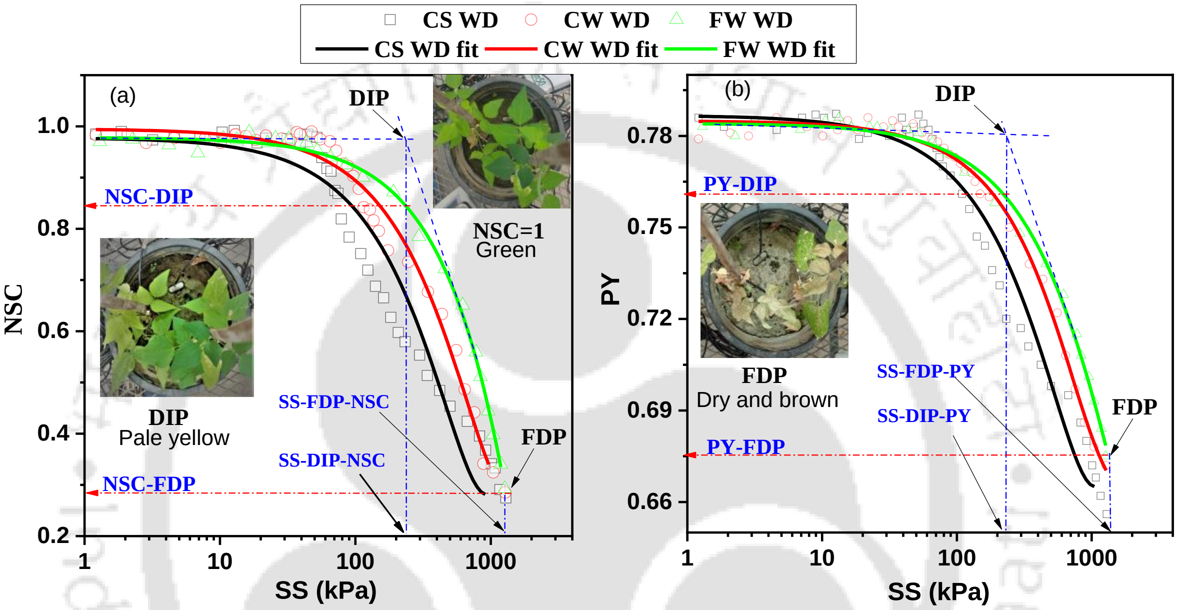


Figure 5.3: Flow diagram depicting the procedure adopted for determining parameters required for studying drought progression in plants under water-deficit condition

The DIP is determined as the point where there is a sharp reduction in NSC/ PY with respect to SS. This is based on the understanding that both SC and PY will reduce due to the initiation of water stress in plants resulting from the difficulty in extracting water from the soil matrix (Gao et al., 2002). The DIP was determined as the point of intersection of double tangents drawn from both ends of the curve as shown in **Figure 5.4**. For this purpose, NSC versus Soil suction curve was fitted to the measured data. The same procedure was repeated for PY versus SS curve. The DIP was further confirmed by the visual interpretation of leaf colour turning pale yellow corresponding to this time (leaf image shown as DIP in **Figure 5.4**). The leaf colour of well-watered plants without drought stress was green (leaf image shown as NSC = 1 in **Figure 5.4**). The FDP was considered as the point where the leaves have dried, turned brown and further measurements of SC and PY is not possible (leaf image shown as FDP in **Figure 5.4**). The SS, NSC and PY corresponding to DIP and FDP were determined for all the combinations considered in this study. A summary of parameters considered further for studying drought progression in plants are given in **Figure 5.3**, and its values from all the measurements are listed in **Table 5.4**.



Note: NSC=$\frac{\text{Stomatal conductance at time t}}{\text{Maximum stomatal conductance}}$, NSC = Normalized stomatal conductance, PY= Photosynthetic yield, DIP = drought initiation point, FDP= final drought point, SS=soil suction

Figure 5.4: (a) NSC (b) PY versus soil suction (SS) plots and method for determining DIP, FDP for beans grown in silt loam

It is evident that there are two SS values corresponding to DIP or FDP emerging from NSC and PY plots. Therefore, it is important to understand whether SS values corresponding to DIP or FDP are unique for a specific combination irrespective of the measured plant physiological parameter (SC or PY) based on which it was determined. The **Figure 5.5** depicts the comparison between SS-DIP-PY and SS-DIP-NSC as well as SS-FDP-PY and SS-FDP-NSC. It can be noted that SS corresponding to DIP from PY and NSC falls close to the 1:1 line. The slope of linear fit passing through origin is 1.006 for the data SS-DIP-PY versus SS-DIP-NSC. Similarly, the data from SS-FDP-PY versus SS-FDP-NSC exactly falls on 1:1 line. Therefore, it can be concluded that there is no difference

Table 5.4 : Details of NSC, PY and SS corresponding to DIP and FDP for (a) silt loam-beans, (b) silt-beans, (c) silt loam-radish (d) silt-radish

(a)

SILT LOAM	BEANS		DIP				FDP			
			SS (kPa)	NSC	SS (kPa)	PY	SS (kPa)	NSC	SS (kPa)	PY
CS	Pot 1	Plant 1	190	0.775	194	0.738	1277	0.246	1275	0.666
		Plant 2	190	0.776	194	0.739	1277	0.243	1275	0.662
	Pot 2	Plant 1	178	0.774	191	0.743	1270	0.248	1279	0.667
		Plant 2	178	0.776	191	0.736	1270	0.24	1279	0.663
CSO	Pot 3	Plant 1	196	0.778	199	0.738	1283	0.249	1289	0.669
		Plant 2	196	0.776	199	0.742	1283	0.245	1289	0.664
	Pot 4	Plant 1	201	0.778	205	0.748	1274	0.251	1282	0.667
		Plant 2	201	0.777	205	0.741	1274	0.248	1282	0.666
CW	Pot 5	Plant 1	215	0.823	210	0.742	1285	0.258	1287	0.669
		Plant 2	215	0.825	210	0.738	1285	0.253	1287	0.671
	Pot 6	Plant 1	208	0.825	218	0.744	1276	0.249	1293	0.666
		Plant 2	208	0.824	218	0.739	1276	0.255	1293	0.668
CWO	Pot 7	Plant 1	216	0.827	220	0.741	1283	0.266	1292	0.673
		Plant 2	216	0.829	220	0.742	1283	0.261	1292	0.67
	Pot 8	Plant 1	234	0.826	225	0.749	1294	0.259	1302	0.668
		Plant 2	234	0.827	225	0.747	1294	0.269	1302	0.665
FW	Pot 9	Plant 1	224	0.825	236	0.748	1302	0.273	1304	0.668
		Plant 2	224	0.824	236	0.753	1302	0.267	1304	0.675
	Pot 10	Plant 1	232	0.825	227	0.748	1292	0.269	1298	0.671
		Plant 2	232	0.834	227	0.744	1292	0.272	1298	0.674
FWO	Pot 11	Plant 1	238	0.834	232	0.748	1299	0.28	1301	0.672
		Plant 2	238	0.834	232	0.757	1299	0.274	1301	0.677
	Pot 12	Plant 1	229	0.829	238	0.751	1308	0.279	1310	0.673
		Plant 2	229	0.829	238	0.755	1308	0.276	1310	0.675

(b)

SILT	BEANS		DIP				FDP			
			SS (kPa)	NSC	SS (kPa)	PY	SS (kPa)	NSC	SS (kPa)	PY
CS	Pot 1	Plant 1	146	0.779	152	0.74	1196	0.236	1200	0.661
		Plant 2	146	0.78	152	0.737	1196	0.231	1200	0.66
	Pot 2	Plant 1	143	0.776	161	0.739	1190	0.233	1197	0.666
		Plant 2	143	0.777	161	0.741	1190	0.23	1197	0.663
CSO	Pot 3	Plant 1	148	0.778	154	0.745	1201	0.238	1204	0.669
		Plant 2	148	0.78	154	0.738	1201	0.233	1204	0.663
	Pot 4	Plant 1	150	0.787	152	0.742	1208	0.235	1213	0.666
		Plant 2	150	0.778	152	0.744	1208	0.237	1213	0.667
CW	Pot 5	Plant 1	161	0.81	162	0.747	1207	0.246	1207	0.67
		Plant 2	161	0.813	162	0.751	1207	0.249	1207	0.668
	Pot 6	Plant 1	164	0.799	159	0.75	1216	0.239	1219	0.667
		Plant 2	164	0.803	159	0.748	1216	0.241	1219	0.668
CWO	Pot 7	Plant 1	174	0.809	164	0.752	1213	0.257	1211	0.669
		Plant 2	174	0.816	164	0.747	1213	0.251	1211	0.671
	Pot 8	Plant 1	168	0.82	169	0.744	1224	0.264	1225	0.668
		Plant 2	168	0.814	169	0.748	1224	0.271	1225	0.671
FW	Pot 9	Plant 1	173	0.821	172	0.75	1227	0.265	1229	0.67
		Plant 2	173	0.827	172	0.748	1227	0.268	1229	0.673
	Pot 10	Plant 1	178	0.819	190	0.752	1223	0.277	1231	0.669
		Plant 2	178	0.8333	190	0.747	1223	0.271	1231	0.674
FWO	Pot 11	Plant 1	181	0.829	192	0.751	1226	0.269	1227	0.672
		Plant 2	181	0.823	192	0.749	1226	0.273	1227	0.677
	Pot 12	Plant 1	174	0.834	186	0.753	1231	0.285	1235	0.675
		Plant 2	174	0.831	186	0.749	1231	0.281	1235	0.671

(c)										
Silt loam	**Radish**		**DIP**				**FDP**			
			SS (kPa)	**NSC**	**SS (kPa)**	**PY**	**SS (kPa)**	**NSC**	**SS (kPa)**	**PY**
CS	Pot 1	Plant 1	167	0.738	171	0.724	1017	0.225	1021	0.419
		Plant 2	167	0.736	171	0.721	1017	0.221	1021	0.42
	Pot 2	Plant 1	160	0.739	176	0.726	1010	0.227	1028	0.417
		Plant 2	160	0.735	176	0.722	1010	0.22	1028	0.42
CSO	Pot 3	Plant 1	165	0.742	182	0.726	1016	0.228	1025	0.419
		Plant 2	165	0.739	182	0.729	1016	0.223	1025	0.418
	Pot 4	Plant 1	174	0.741	177	0.723	1025	0.231	1029	0.421
		Plant 2	174	0.739	177	0.725	1025	0.237	1029	0.418
CW	Pot 5	Plant 1	183	0.745	188	0.727	1024	0.241	1031	0.421
		Plant 2	183	0.743	188	0.726	1024	0.238	1031	0.419
	Pot 6	Plant 1	176	0.748	191	0.729	1028	0.247	1037	0.423
		Plant 2	176	0.749	191	0.73	1028	0.249	1037	0.418
CWO	Pot 7	Plant 1	181	0.746	189	0.731	1031	0.251	1029	0.422
		Plant 2	181	0.753	189	0.728	1031	0.246	1029	0.42
	Pot 8	Plant 1	188	0.751	196	0.733	1026	0.255	1033	0.419
		Plant 2	188	0.758	196	0.73	1026	0.249	1033	0.423
FW	Pot 9	Plant 1	185	0.763	202	0.734	1032	0.261	1041	0.426
		Plant 2	185	0.768	202	0.729	1032	0.257	1041	0.423
	Pot 10	Plant 1	193	0.759	194	0.733	1029	0.254	1036	0.424
		Plant 2	193	0.77	194	0.73	1029	0.259	1036	0.421
FWO	Pot 11	Plant 1	194	0.777	199	0.732	1031	0.262	1044	0.426
		Plant 2	194	0.771	199	0.736	1031	0.259	1044	0.423
	Pot 12	Plant 1	187	0.775	209	0.731	1036	0.261	1039	0.429
		Plant 2	187	0.769	209	0.735	1036	0.265	1039	0.425

(d)

Silt	**Radish**		**DIP**				**FDP**			
			SS (kPa)	**NSC**	**SS (kPa)**	**PY**	**SS (kPa)**	**NSC**	**SS (kPa)**	**PY**
CS	Pot 1	Plant 1	132	0.737	134	0.718	946	0.217	947	0.419
		Plant 2	132	0.735	134	0.716	946	0.215	947	0.416
	Pot 2	Plant 1	125	0.739	139	0.715	940	0.22	952	0.415
		Plant 2	125	0.734	139	0.716	940	0.212	952	0.417
CSO	Pot 3	Plant 1	129	0.736	136	0.719	953	0.225	957	0.419
		Plant 2	129	0.74	136	0.723	953	0.221	957	0.421
	Pot 4	Plant 1	137	0.739	145	0.718	948	0.228	949	0.418
		Plant 2	137	0.743	145	0.721	948	0.23	949	0.422
CW	Pot 5	Plant 1	151	0.743	156	0.724	963	0.229	964	0.42
		Plant 2	151	0.748	156	0.72	963	0.234	964	0.423
	Pot 6	Plant 1	146	0.741	149	0.727	956	0.231	969	0.419
		Plant 2	146	0.745	149	0.725	956	0.231	969	0.418
CWO	Pot 7	Plant 1	159	0.76	154	0.729	959	0.237	966	0.421
		Plant 2	159	0.754	154	0.724	959	0.233	966	0.424
	Pot 8	Plant 1	154	0.763	161	0.73	968	0.241	974	0.427
		Plant 2	154	0.756	161	0.726	968	0.235	974	0.423
FW	Pot 9	Plant 1	157	0.758	168	0.731	973	0.256	971	0.426
		Plant 2	157	0.767	168	0.728	973	0.253	971	0.428
	Pot 10	Plant 1	163	0.761	159	0.725	969	0.252	979	0.427
		Plant 2	163	0.765	159	0.727	969	0.256	979	0.43
FWO	Pot 11	Plant 1	161	0.769	164	0.732	984	0.258	993	0.428
		Plant 2	161	0.764	164	0.729	984	0.251	993	0.428
	Pot 12	Plant 1	166	0.771	175	0.734	981	0.257	985	0.431
		Plant 2	166	0.768	175	0.731	981	0.26	985	0.429

in SS corresponding to DIP/ FDP obtained based on PY and NSC. This observation endorses the fact that both SC and PY based on two different measurement methodologies capture DIP and FDP in an identical manner (same SS). The observation demonstrates that both the plant attributes representing drought (DIP and FDP) has unique relation with water potential in soil (SS). The overall variation of SS-DIP and SS-FDP is in the range 125-238 kPa and 940-1310 kPa, respectively considering all the observations from this study. The range of values may be attributed to the influence of plant type, soil-plant combination and soil amendment, which is investigated below.

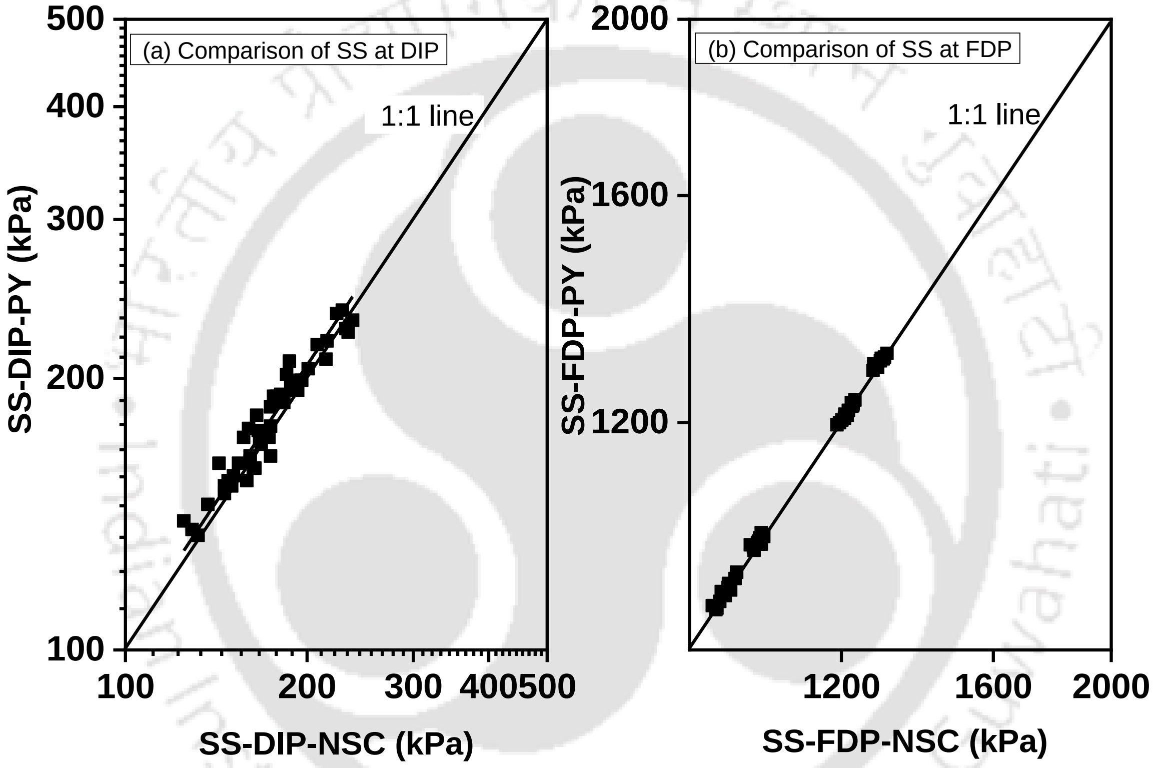


Figure 5.5: Comparison of SS corresponding to (a) DIP (b) FDP determined based on PY and NSC.

Figure 5.6 relates SS at FDP to SS at DIP obtained from both NSC and PY. The aim is to explore whether it is possible to estimate SS at FDP (point of permanent wilting) knowing the SS at DIP. It may be noted from **Figure 5.2** that the time taken for observing DIP is less than 10 days where as time taken to reach FDP is more than 25 days. Hence, a relationship to estimate SS at FDP is handy to anticipate the permanent wilting condition much in advance with the help of soil suction measurement sensors deployed in the field. It can be noted from **Figure 5.6** that the relationship between SS at FDP and DIP follows a linear trend based on both NSC and PY measurements. An interesting observation is that the relationship is influenced by plant type. Hence, separate linear relationship was determined and shown on the plot with an $R^2 > 0.8$. It can be clearly seen that the range of SS-FDP for beans is distinctly higher than radish. At the same time SS-DIP for both the species overlap and varies within a small range with beans exhibiting marginally higher values. This indicates that SS-FDP was more specifically dependent on plant species than SS-DIP.

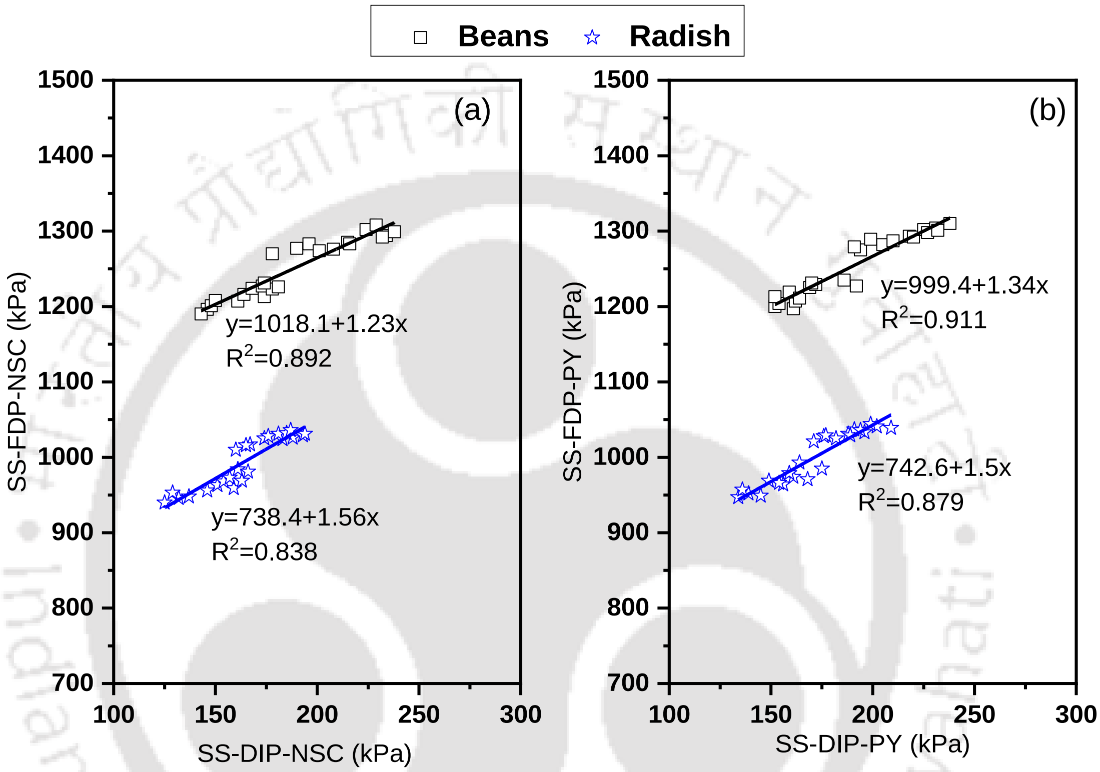


Figure 5.6: Relationship between SS at FDP and SS at DIP corresponding to (a) NSC (b) PY

The relationship between NSC, PY at FDP and DIP is shown in **Figure 5.7**. Similar to SS, NSC and PY also exhibit a linear trend shown in the Figure The results of PY shows scatter and hence a poor R^2 value compared to NSC. Both the relationships are dependent on plant species where in PY-FDP was distinctly different for both the species compared to NSC-FDP. Both NSC-DIP and PY-DIP showed considerable overlap for both species with radish showing lower values than beans. However, NSC and PY at FDP was higher for beans than radish. A detailed discussion on the influence of plants species on observed attributes is presented below. At this stage of research, the study only demonstrates the possibility of developing such correlation for estimating plant attributes related to permanent wilting based on initial observations. Further studies are needed with diverse plant species and soil-plant combinations for generalizing the findings and obtaining the appropriate regression parameter values for determining the attributes at permanent wilting knowing the values at drought initiation.

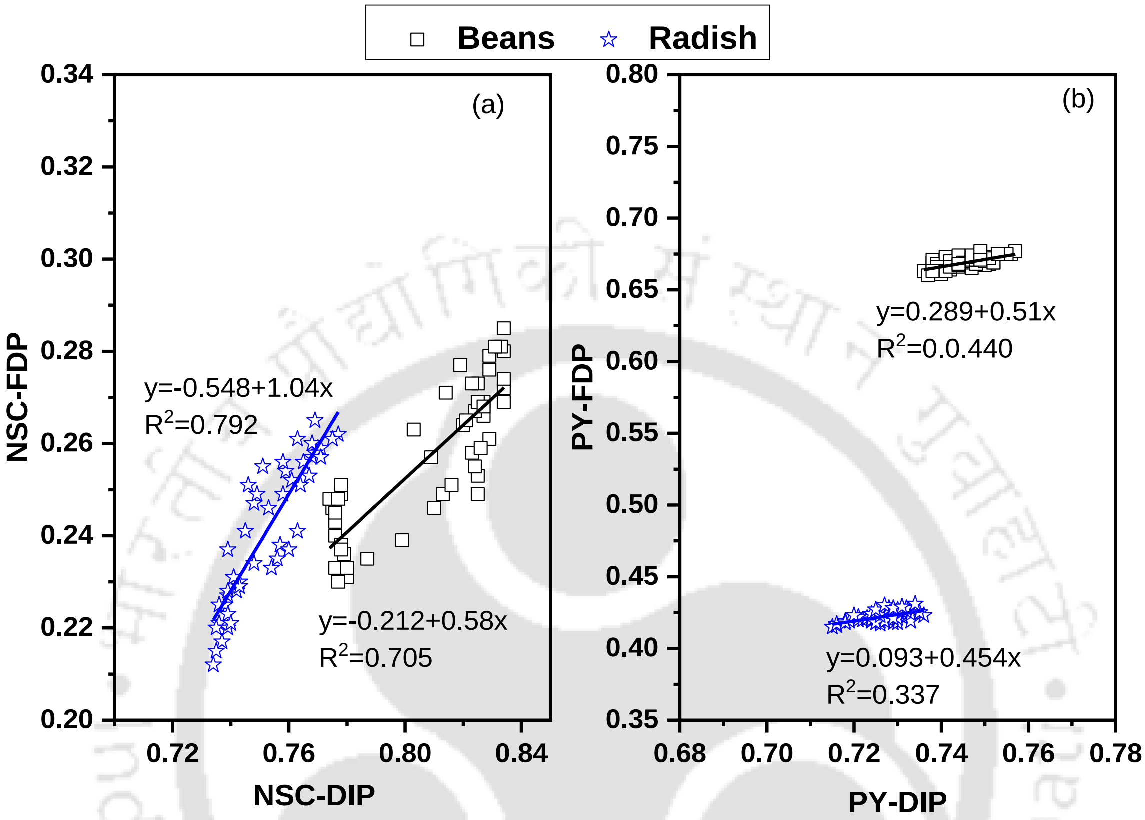


Figure 5.7: Relationship between (a) NSC at FDP and DIP (b) PY at FDP and DIP

The following discussions specifically aims to understand the influence of soil type, plant species and soil amendment on drought related parameters listed in **Figure 5.4**, considering each separately. **Figure 5.8** shows the values of all the drought related parameters of silt plotted on y axis and silt loam on x axis. All are square plots with 1:1 line marked on it for comparing the data. The data close to 1:1 line indicate negligible influence of soil type on the specific drought parameter. Among all, only SS-DIP exhibited marginal difference due to soil type. It may be noted that SS-DIP and SS-FDP obtained from NSC and PY were combined because it gave identical values **(Figure 5.5).** It was noted that SS-DIP of silt was 0.95 times SS-DIP of silt loam for beans and 0.96 times for radish, which can be considered as a marginal difference. All other drought related parameters of silt and silt loam, SS-FDP, NSC-DIP, NSC-FDP, PY-FDP, matched well. The PY-DIP of beans showed negligible dispersion of data about 1:1 line. The observation from **Figure 5.8** clearly indicates that soil type has negligible role on the determination of

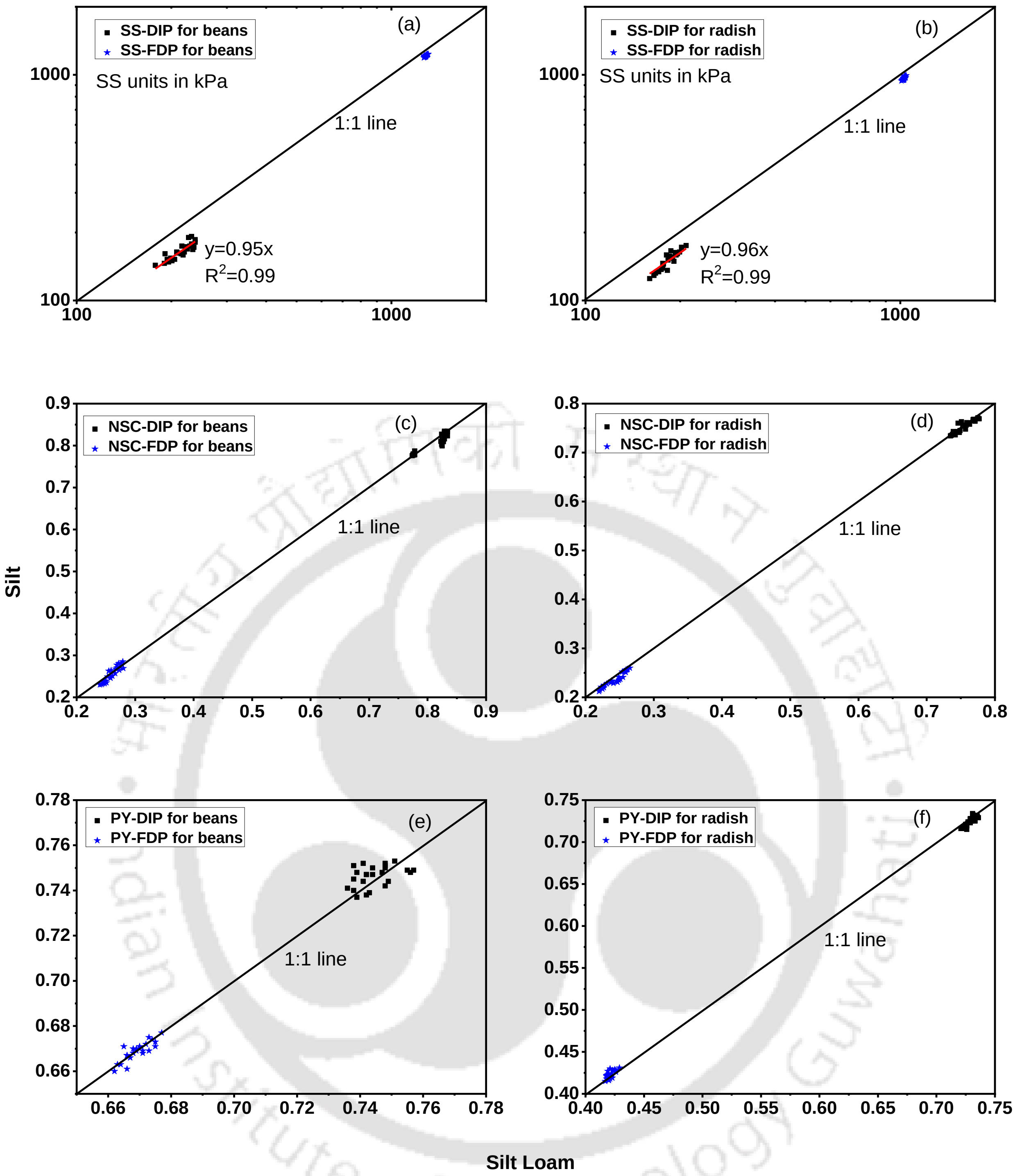


Figure 5.8: Influence of soil type on SS at DIP and FDP for (a) beans (b) radish, NSC at DIP and FDP for (c) beans (d) radish, PY at DIP and FDP for (e) beans (f) radish

drought related parameters defined in this study. It is important to confirm this observation for other soil textures as well. It is already stated in the literature that the permanent wilting point (measured suction in soil) can be different for different textures (Wiecheteck et al., 2020). Therefore, the findings related to the influence of soil type from this study is restricted to only two soil textures (commonly adopted growth medium) and cannot be generalized at this stage.

The influence of plant type on SS, NSC and PY corresponding to DIP and FDP is presented in **Figure 5.9**. It is explicit that all the drought related parameters are affected by plant type. Among all, the major difference was observed for PY-DIP of radish, which is 0.63 times that of beans for both the soil type. The SS-DIP and SS-FDP of radish was marginally less by 0.97-0.98 times than beans, which is the least influenced by soil type.

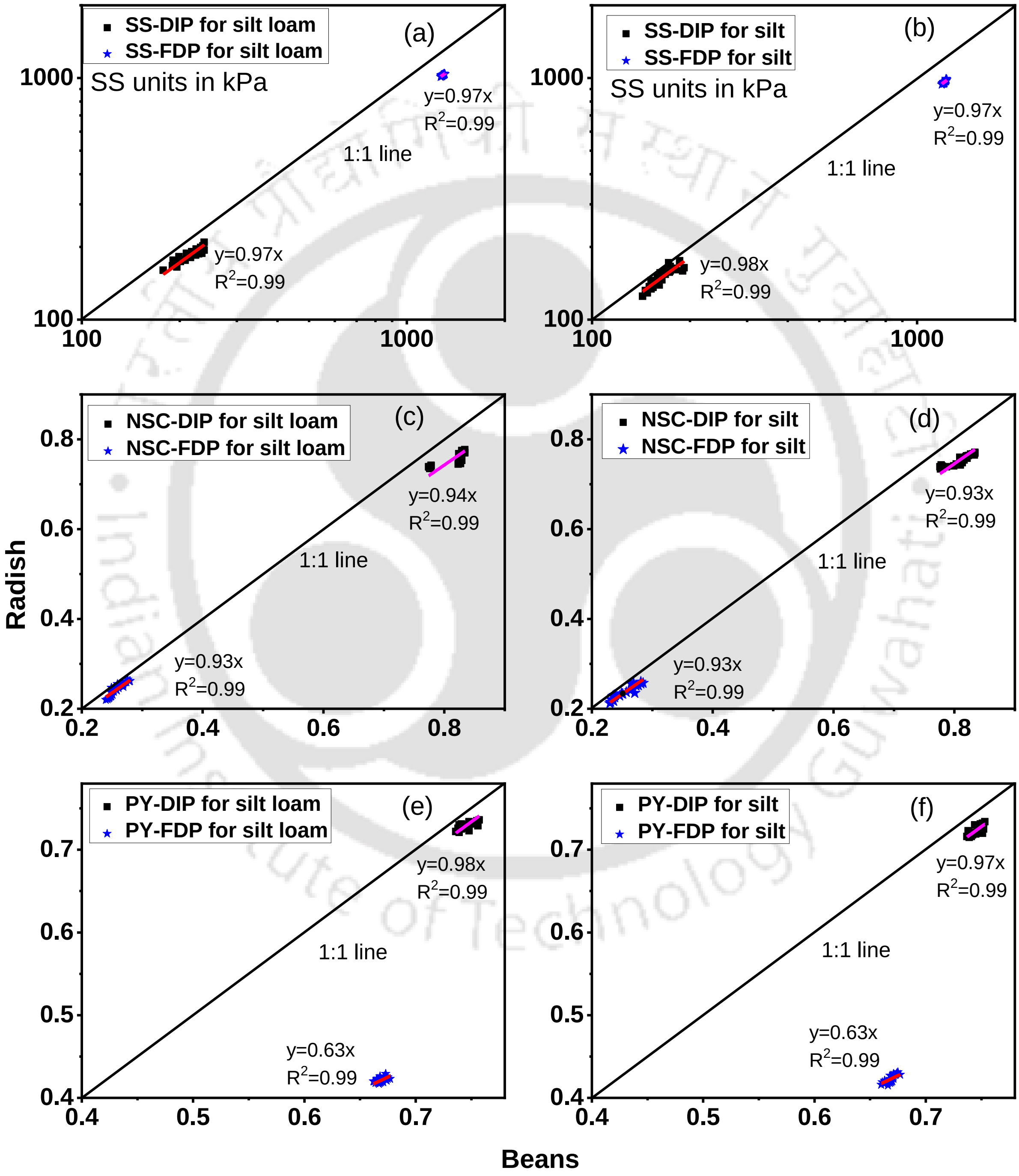
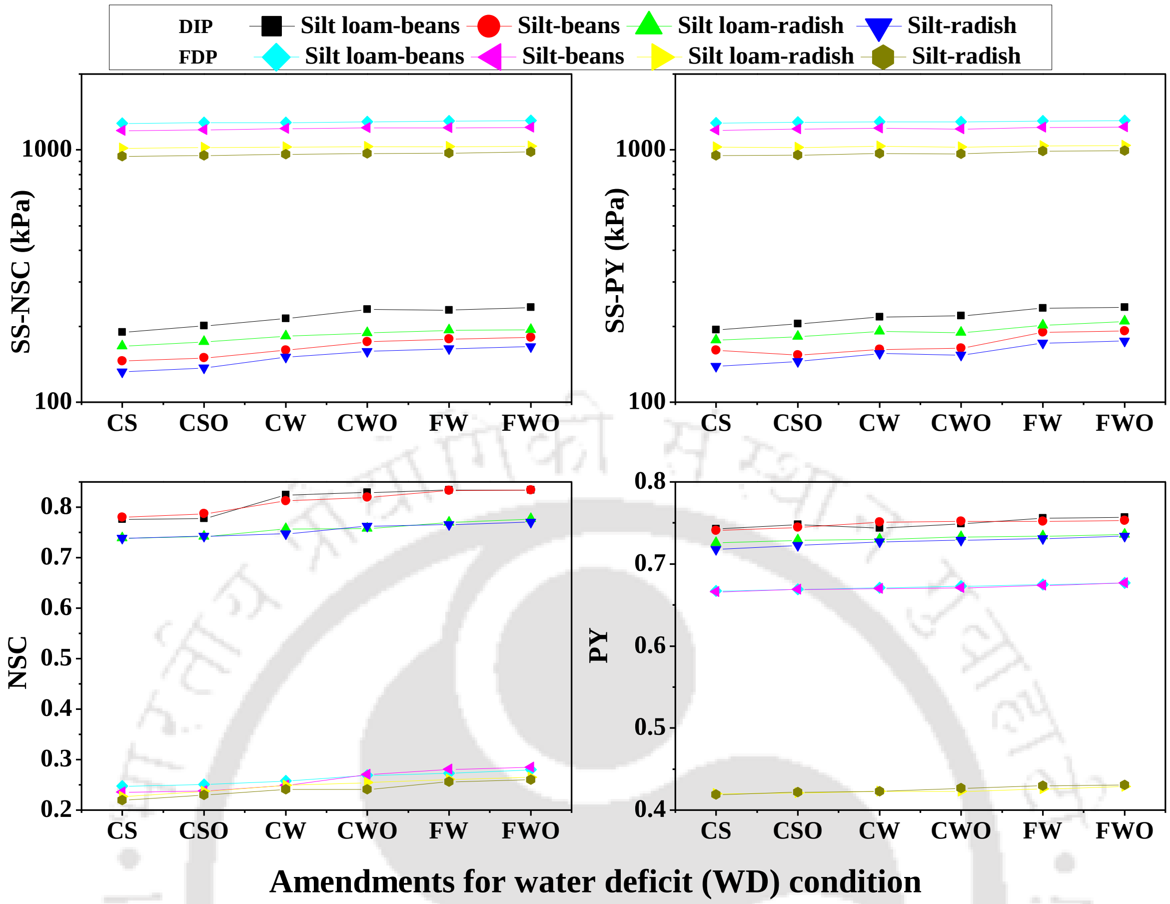


Figure 5.9: Influence of plant type on SS at DIP and FDP for (a) silt loam (b) silt, NSC at DIP and FDP for (c) silt loam (d) silt PY at DIP and FDP for (e) silt loam (f) silt

The NSC-DIP, NSC-FDP was 0.93-0.94 times than beans. The PY-DIP was only marginally influenced (0.97-0.98 times) by plant type. Compared to soil type, it can be concluded that plant species has predominant role in the determination of parameters than can assess the progression of drought stress in plants. This points to the fact that the range of drought stress parameters should be specifically determined for any given plant type.

Figure 5.10 presents the influence of different soil amendments (**Table 5.1**) corresponding to water-deficit condition on drought related parameters. The SS-DIP showed a marginal increase for WAP amended soils and practically same SS-FDP for different amendments. The NSC-FDP also exhibited a marginal rising trend for WAP amended soil and practically identical values of PY-DIP, NSC-DIP and PY-FDP for all amendments. This observation may be true due to the fact that the drought parameters are affected by the status of water in the soil and the corresponding root uptake. The values of NSC and PY corresponding to a given water stress (DIP and FDP) should be identical for all amendments because this is predominantly influenced by plant type. However, the time at which DIP and FDP reaches is influenced by different amendments. The onset of DIP and FDP can be delayed in soil amended with WAP due to its better water storage. This is explicit by the fact that permanent wilting time is increased for WAP amended soil as reported in the literature (Ashraf et al., 2021; Saini et al., 2022).

The range of drought related parameters considering all the amendments are summarized in **Table 5.5**. As already stated earlier (**Figure 5.8**), the range of SS-DIP is marginally different for two different soil textures. Neglecting the soil type, the overall variation of SS-DIP for beans and radish are 143-238 kPa and 125-209 kPa, respectively. The SS-FDP for beans is 1190-1310 kPa and for radish it is 940-1044 kPa. The NSC-DIP showed a unique range of 0.734-0.834 considering all plant type, soil type and soil amendments. Similarly, NSC-FDP was in the range of 0.215-0.285. The overall range of PY-DIP was 0.715-0.757, which was similar to the NSC-DIP range. Unlike NSC-FDP, the PY-FDP range was influenced by plant type with beans exhibiting a range of 0.660-0.677 and 0.415-0.431 for radish. It was not possible to cross-verify these findings from the literature because the parameters defined related to drought progression was specific to this study and first of its kind. Therefore, more studies with different plant-soil combinations are needed to generalize the findings from this study.



Note: Refer to Table 1 for abbreviation on x axis

Figure 5.10: Influence of soil amendment on (a) SS at DIP and FDP from NSC (b) SS at DIP and FDP from PY (c) NSC at DIP and FDP (d) PY at DIP and FDP

Table 5.5: The summary of drought related parameters considering all the soil amendments

Drought parameter	**Silt loam**		**Silt**	
	Beans	**Radish**	**Beans**	**Radish**
SS-DIP (kPa)	173-238	160-209	143-181	125-175
SS-FDP (kPa)	1277-1310	1010-1044	1190-1235	940-993
NSC-DIP	0.775-0.834	0.738-0.777	0.776-0.834	0.734-0.771
NSC-FDP	0.240-0.280	0.220-0.265	0.230-0.285	0.215-0.260
PY-DIP	0.738-0.757	0.721-0.736	0.737-0.753	0.715-0.734
PY-FDP	0.662-0.677	0.418-0.429	0.660-0.677	0.415-0.431

Due to a deficiency of water availability, plants commence signalling transmission regarding changes in the functioning of stomata (Jia and Zhang, 2008). To maintain the functioning of stomata which requires irrigation, without interfering with plant growth and productivity (Sanandam et al., 2022).

SC and PY are affected by plant type and soil water availability/status (Wong et al., 1979). Whereas soil suction is influenced by soil type and plant species (Leung and Ng, 2019). Water deficiency conditions cause a decrease in SC and PY with increasing suction, which promotes stomatal closure via signal transmission to plant hormones (Tipple and Pagani, 2007).

5.3.1.4) Crop yield in two different soils and WAPs under water stress

The crops with high yield are desirable for ensuring food security under the threat of climate change, global warming and water availability (Geeroms et al., 2008). The **Figure 5.11** depicts important yield parameters for beans and radish grown in control and with different amendments. Under drought stress (water-deficit condition), the crop yield has increased with WAP amendment in addition to well-water conditions. The following is the ascending order of total weight and number of beans under drought stress and well-water condition: CS < CSO < CW < FW < CWO < FWO. The total weight of beans increased to 3.25 times (silt loam) and 3.67 times (silt) under drought stress condition for FWO amendment compared to CS. Similarly, the total weight of radish increased 3.1 times (silt loam) and 3.24 times (silt) under drought stress condition for FWO amendment. The study demonstrates the effectiveness of WAP amendment to maintain/ increase crop yield under water stress condition.

Comparison of yield and survival time

WAP amendment enhanced survival time and yield more in silt (around 3 times for yield and 2 times for survival time in WAP to control) than silt loam (2.6 times for yield and 1.7 times for survival time in WAP to control) under drought stress for beans species. Under drought stress, the increasing factor for survival time was greater in silt (2.3 times in WAP) than silt loam (1.8 times in WAP), and the increasing factor for yield was almost equivalent in both soil with the WAP amendment in radish. It is observed that the silt loam is more suitable for beans with WAP addition than silt because it has a longer plant survival period and yield under well-watered conditions and drought stress. This study reveals that the bean species produces more yield in silt loam, whereas radish has an approximately similar yield in both soils. Furthermore, the WAP amendment has a greater influence on silt and bean species compared to silt loam and radish, which helps to reduce watering frequency while maintaining crop yield.

5.3.2) Field experiments

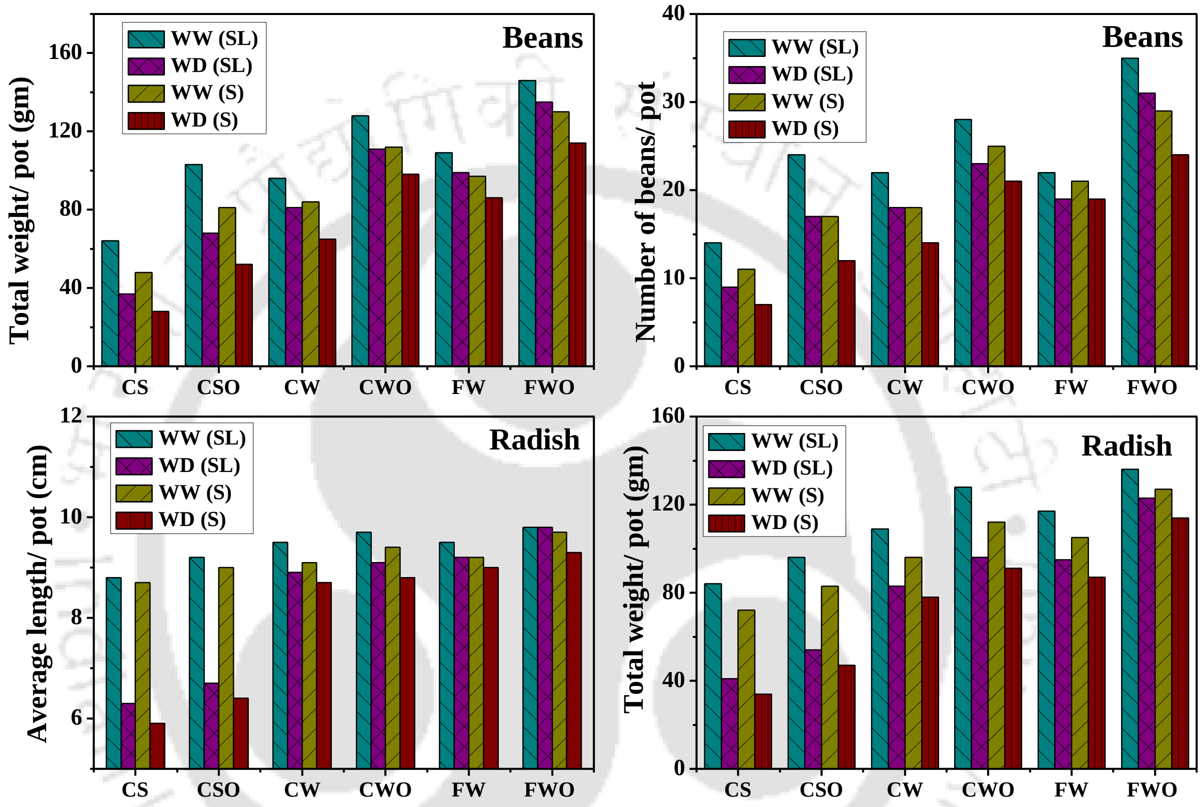
5.3.2.1) Beans and Radish

5.3.2.1.1) General

The soil in the selected plot area was loosened, cleaned and unwanted roots were removed up to a depth of 30 cm. The preparation of soil in the field was done by adhering to the procedure for soil preparation in the field. A spade was used to loosen the soil up to a depth of 30 cm. The soil should maintain a loosened state without the imposition of external compaction forces. The dry WAP was evenly applied to the loosened soil surface and mixing with the spade continuously for homogeneous mixing (similar to the mixing of fertilizer in soil). The water content of the soil was maintained at 16-17% for all plots during the dry WAP mixing. The plot area was divided into six subplots: two each for FW amendment, CW amendment and Control. Each subplot has an area of 2.1 m^2 (1.2 m x 1.75 m). Each subplot was raised by 10 cm by placing the soil to avoid waterlogging from the surrounding area for bean. In subplot planted with radish, the edge was raised (to prevent direct contact of roots with water), and the central region was used for irrigation. In total 14 plants (seeds) for both beans and radish were germinated in each subplot. The plants were grown until they reached their post-juvenile stage. The irrigation was then stopped and one of the subplots for each treatment (**refer table 5.1**) was subjected to drying or drought condition. The remaining subplots were irrigated with adequate water to maintain well-watered condition. Soil water status in terms of SWCC and plant characteristics (e.g. stomatal conductance, photosynthetic yield, etc.) were monitored during plants' life cycle using sensors discussed in the 5.3.2 section.

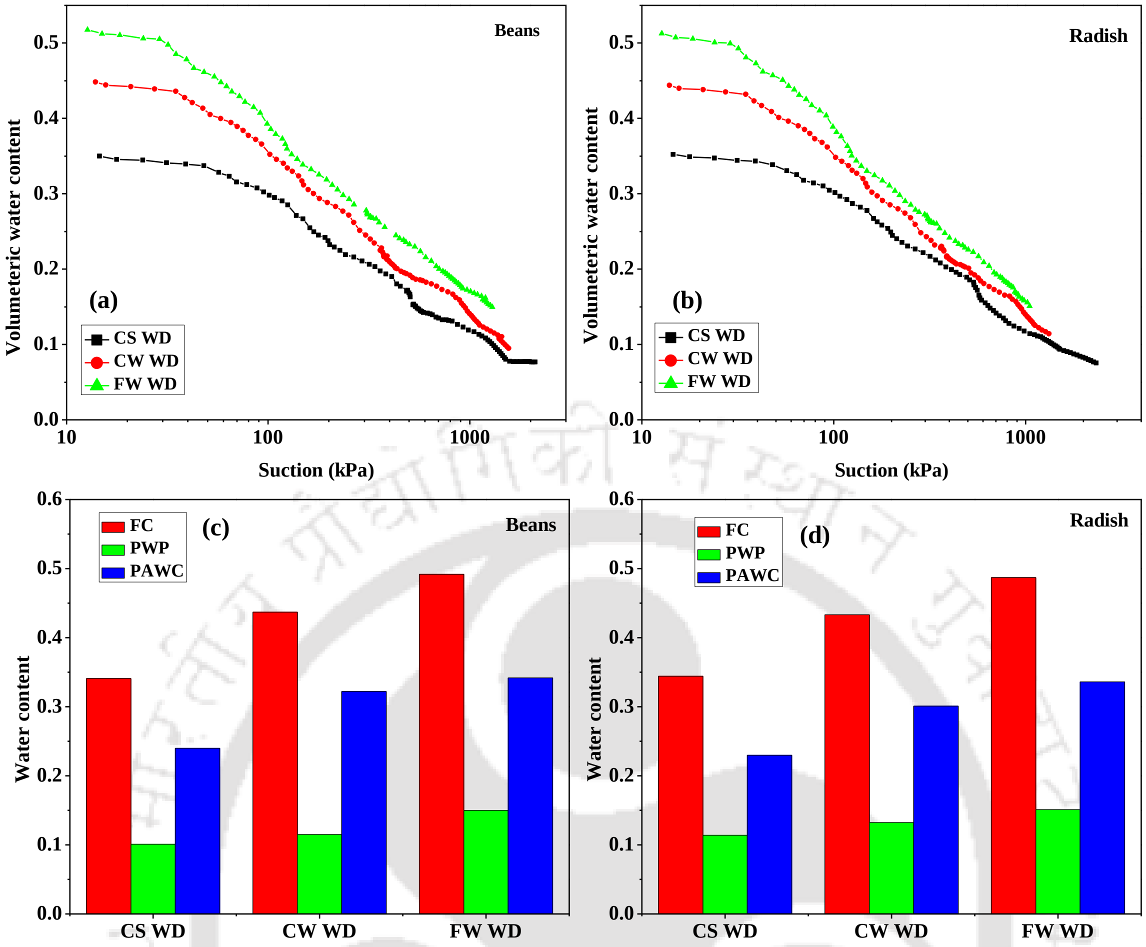
5.3.2.1.2) Effect of WAP on soil water retention behavior

Figures 5.12 (a) and (b) presents the effect of WAPs on soil-water retention curve (SWCC) for bean and radish. The results indicate that the WAP amended soil has improved the water retention properties as compared to control for both plant species. The changes in SWCC is due to the improved water storage within the pore volume of soil matrix. Such a trend was observed for soils amended with WAP reported in the literature (Saha et al., 2020c). The water retention improved more in the lower suction range as compared to the higher suction range. At lower suction, water retention improvement is contributed by the capillary forces and the water stored in the WAP (Rahmati et al., 2019; Saha et al., 2020c). At higher suction, water retention is controlled by specific surface area (SSA) of the soil and adsorptive forces. The amendment of WAP increases the SSA, which helps to bind more water on the soil particle in the form of a thin film (Dorraji et al., 2010; Senna and Botaro, 2017). The improvement in water retention was found to be higher for the FW in the presence of soil and plant species as compared to the CW, despite the fact that water absorbing capacity of the latter was higher than the former. This higher absorbency of FW is due to the presence of aluminosilicate backbone material (fly ash) that improves the mechanical strength of WAP and allows better swelling in soil matrix (Kabiri et al., 2011). Hence, FW is found to be more efficient in enhancing water retention as compared to CW. The water retention trend is similar for both the species. The marginal difference observed may be attributed to the difference in root architecture that can affect the pore volume (Leung et al., 2015).



Note : WW: Well water condition, WD: Water deficit conditon, SL: Silt loam, S: Silt

Figure 5.11: Effect of water-absorbing polymer on yield parameters- (a) total weight of bean, (b) Number of beans, (c) total weight of radish and (d) length of radish



FC = Filed capacity, PWP = Permanent wilting point, PAWC = Plant available water content

Figure 5.12: Influence of water absorbing polymer (WAP) on soil water retention behaviour

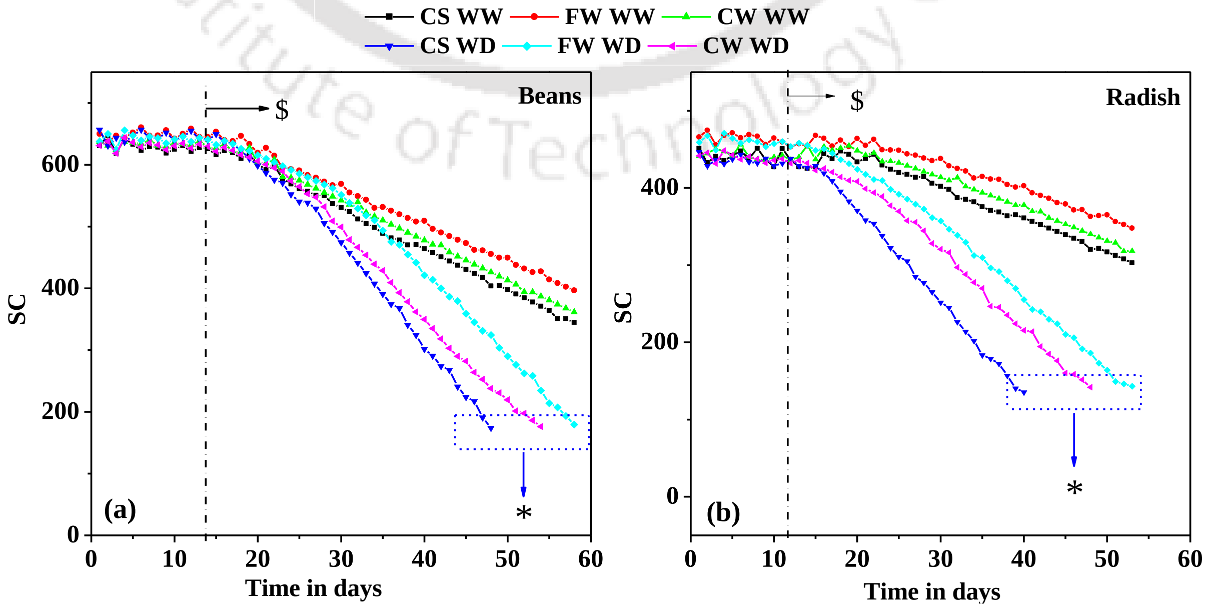
The effect of WAP on field capacity (FC), permanent wilting point (PWP), and plant available water content (PAWC) for both plant species are presented in **Figures 5.12 (c) and (d).** It is noted from the Figure that WAP-amended soil has more FC, PWP, and PAWC as compared to control. For bean species, FW amended soil was found to enhance FC and PAWC by 44% and 43%, respectively, compared to control (refer to **Figure 5.12 (c)**). For CW amended soil FC and PAWC increased by 28% and 35%, respectively. For radish, FW amended soil enhanced FC and PAWC by 41.5 % and 46 %, respectively and for CW, the increase in FC and PAWC was 26% and 30 %, respectively (data **from Figure 5.12 (d)).** It is indicated from results that WAP amended soil has increased the water storage in the soil, which acts as a supplementary water storage micro-reservoir during water stress condition. This helps to maintain plant growth under drought condition. The percentage increment in FC and PAWC was identically close for both the species for the respective

WAP amendment, which indicates the fact that the role of WAP was significant in improving FC and PAWC than the pore structural changes caused by the root structure of the two species.

5.3.2.1.3) Effect of WAP on physiological parameters

Figures 5.13 (a) to (d) shows the variation of SC and PY with time for both bean and radish species for well-watered and water deficit condition. The results show that the SC is higher in the WAP amended soil as compared to the control in the water deficit and well-watered condition. The rate of decrement in SC is more in water deficit condition than well-watered condition. The marginal decreases in SC for well-watered condition was mainly due to healthy leaves (Arbona et al., 2005). The minimum SC was found under water deficit conditions in the range of 174-180 m mol $m^{-2}s^{-1}$ for bean and 135-144 m mol $m^{-2}s^{-1}$ for radish. This difference in minimum SC is expected among different species (Bunce, 2006). Higher SC in plants grown in WAP amended soil implies more transpiration rate, which indicates less water stress in soil. Similarly, Farquhar and Sharkey, (1982) reported that higher transpiration leads to a lower leaf temperature, which assists in maintaining water status. The decrement rate of SC is less with the WAP amendment during water deficit condition, which restricts the gaseous exchange from the leaves, hence reducing the decrement rate of photosynthesis.

The reduction in photosynthesis can be assessed using chlorophyll fluorescence estimated from the maximum quanta yield ratio (F_v/F_m) termed as PY (Maxwell and Johnson, 2000). **Figures 5.13 (c) and (d)** shows that PY was higher in the WAP amended soil as compared to the control for both bean and radish species, indicating higher rate of



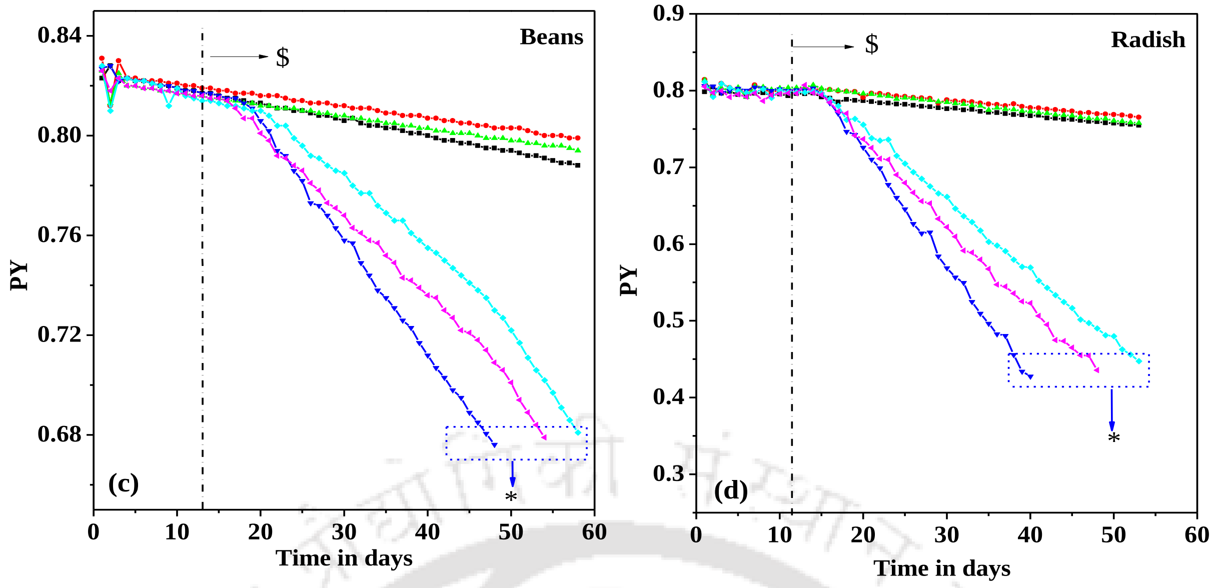


Figure 5.13: Variation of maximum stomatal conductance (SC) and Photosynthetic yield (PY) with time for radish and beans in soil with and without WAP.

Note '$': Irrigation stops for water deficit plots. '*': Minimum measured value of SC and PY represents wilting of plant. The leaf is in dry stage where it is not possible to measure SC and PY

photosynthesis (Oxborough and Baker 1997; Song et al., 2020). The observed minimum value of PY is 0.676-0.681 for bean and 0.428-0.448 for radish under water deficit condition. Garg et al. (2020) reported that the soil pore size can influence the plant photosynthetic rate due to water uptake under continued water deficit condition. Similarly, WAP has also influenced the water availability for plants compared to control by facilitating more water storage in soil pores. This implies that the higher PY is maintained in WAP amended soil as compared to control. Overall WAP has high positive influence on the physiological parameters SC and PY as compared to the control there by enhancing the growth and yield of plants (Barbour et al., 2000).

5.3.2.1.4) Wilting characteristics under water deficit condition

This section focused on understanding wilting characteristics of plant species under water deficit condition. **Figure 5.14** showing the relationship between SC and PY with soil suction was used to characterize wilting in terms of drought initiation point (DIP) and final drought condition (FDC). Drought initiation point represents the point where the plants experience difficulty in extracting water from the soil. The DIP was obtained by drawing tangents from both ends of SC vs suction and PV vs suction curves. The point of intersection of the two tangents is considered as DIP. The DIP was further interpreted using the visual interpenetration of plant leaves status. Based on SC versus suction curve, DIP for bean lies between 220 and 250 kPa while it lies between 210 and 240 kPa based on PY versus suction curve. Similarly, for radish, DIP lies between 175-200 kPa and 180-210 kPa based on SC versus suction and PY versus suction relationships, respectively.

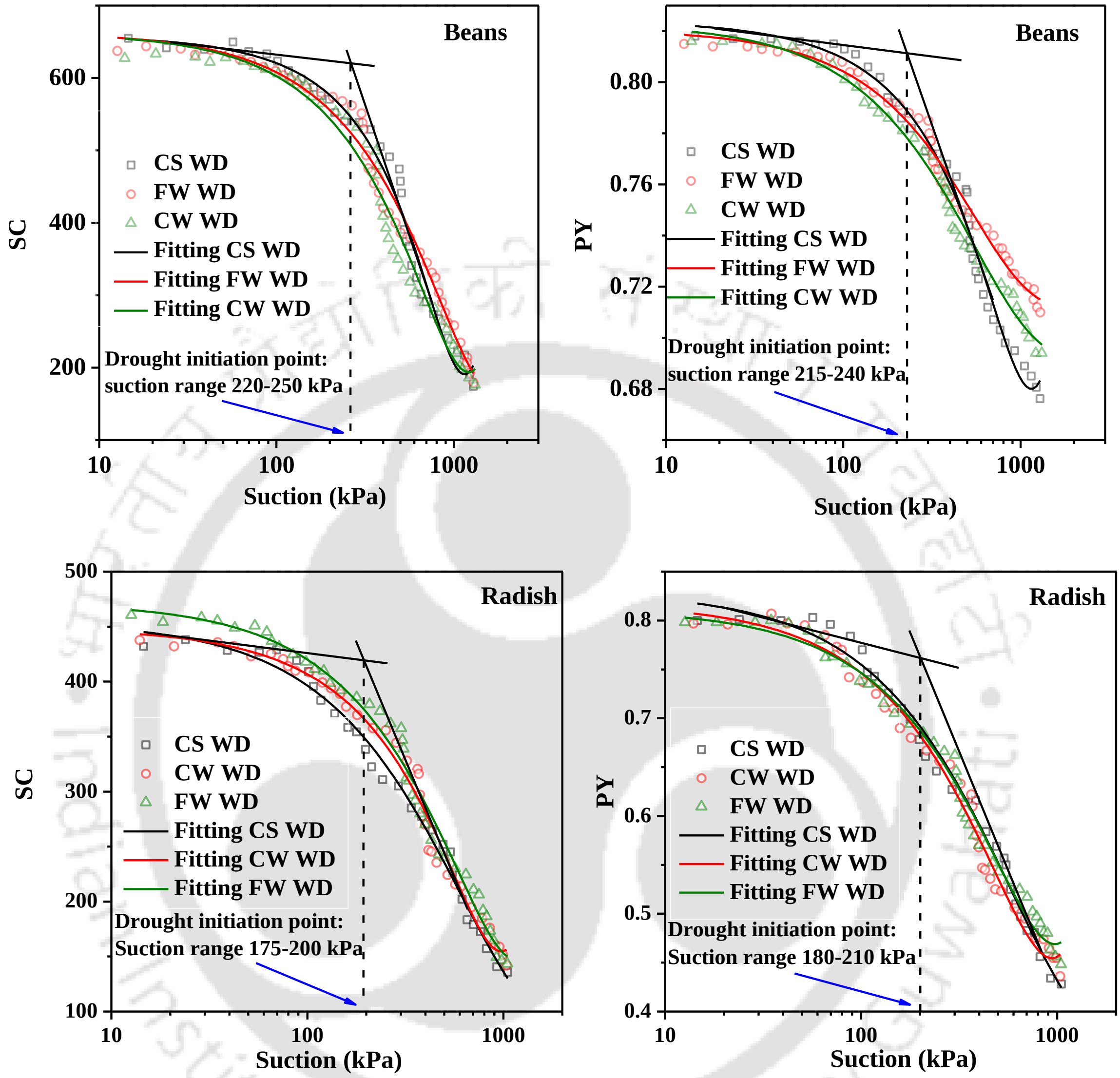


Figure 5.14: Relationship of SC and PY with suction for the determination of drought initiation point.

Note: Point of tangency is shown here only for control. Details of suction value of all treatments is presented in **table 5.6**

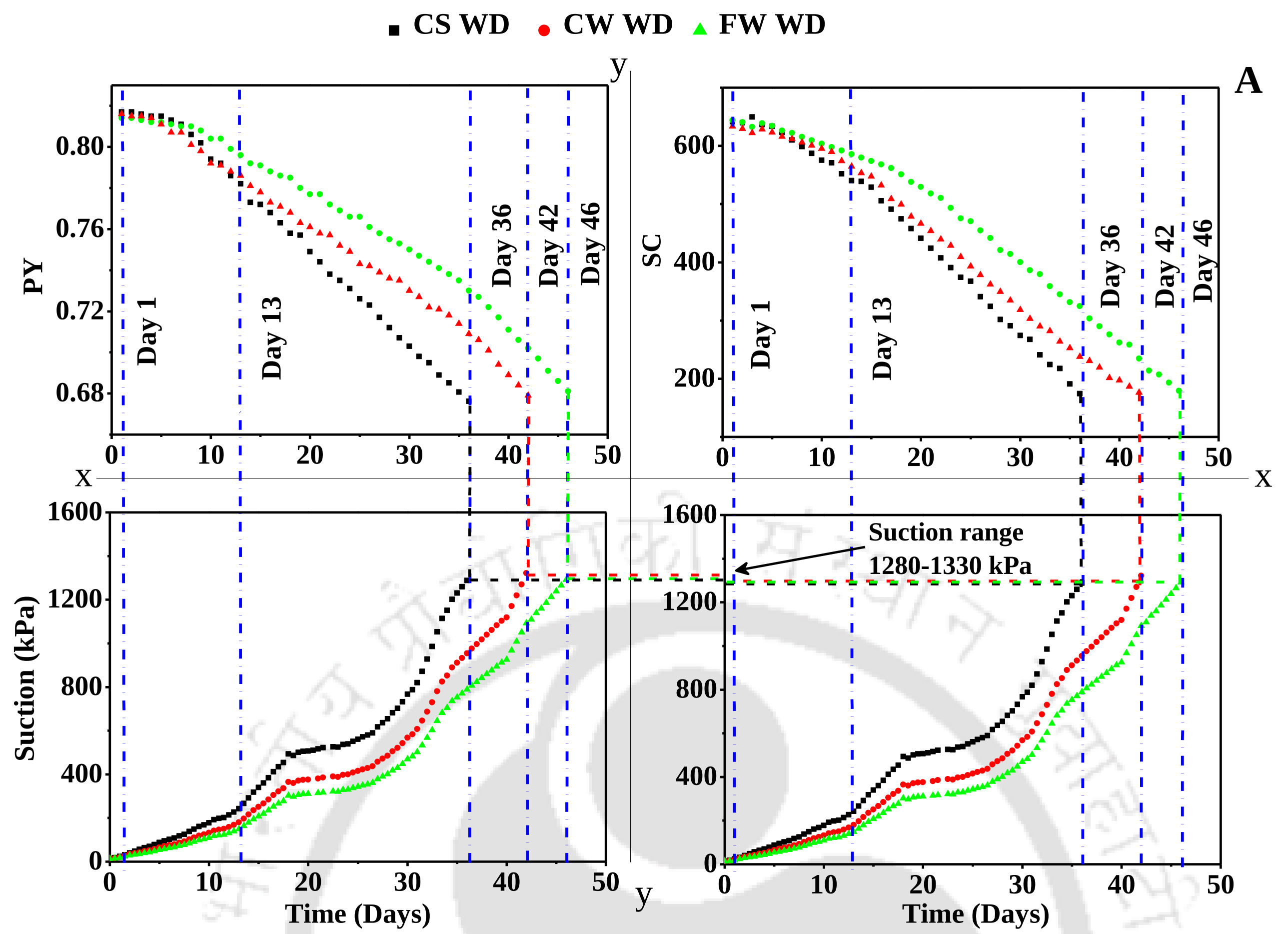
For the sake of brevity, the tangent construction for DIP determination has been shown in **Figure 5.14** for the control condition only. The same procedure was adopted and the values of DIP are summarized in **Table 5.6**. The overall suction range of DIP is 215-250 kPa for bean and 175-211 kPa for radish. The drought initiation point is nearly the same for all the treatments (WAP amended soil and control condition). The DIP was also found to be consistent with the change in leaf colour, as shown in **Figures 5.15 and 5.16**

(Image- Day 13 for bean and day 11 for radish in control condition). From this point, the plant physiological parameters (SC and PY) start deteriorating. This is the point, where water shortage occurs in plants and irrigation is ideally needed (Sanandam et al., 2022). This threshold suction range can be considered unique for a particular soil type-plant species combination. Further studies are need to establish its uniqueness for different soil texture-plant species combination.

Figures 5.15 and 5.16 presents the wilting pattern (from the saturated to dry stage) by linking soil suction with the physiological parameters of plant at different growth stages for bean and radish, respectively. These relationships can be used for estimating the PWP during drought condition for the WAP amended soil and control. The soil suction at PWP was 1280-1330 kPa corresponding to a minimum SC (174-180 m mol $m^{-2}s^{-1}$) and PY (0.676-0.681) for bean. For radish, PWP was 1030-1060 kPa for a minimum SC (135-144 m mol $m^{-2}s^{-1}$) and PY (0.428-0.448). Due to water deficit condition, SC and PY decreases with an increasing suction. During this stage, there is transmission of signal to plant hormone that leads to stomata closure (Tipple and Pagani, 2007). This results in minimum root water uptake from soil, which further diminishes the chlorophyll pigment in leaves. **Figure 5.15(b) and 5.16(b)** demonstrates the leaf status (chlorophyll content) with suction at different stages of water deficit. The leaf color pattern changed from green to yellow with an increasing soil suction (i.e. saturated stage to dry stage). Similarly, Zhu (2007) and Garg et al. (2020) reported that the chlorophyll content decreases with an increase in the leaf water potential for oak and grass species, respectively, under water deficit condition. The clampdown of chlorophyll towards wilting point due to the termination of reactions result in significant reduction of SC and PY. The PWP marks the soil water content, below which plant cannot survive leading to plant death. The details of suction values at PWP are summarized in **Table 5.7** based on the minimum measured values of SC, PY and visual interpretation.

5.3.2.1.5) Effect of WAP on Yield parameters

All agricultural practices and modernizations aim to increase crop yield even if environmental conditions are not suitable. As shown in **Figure 5.17**, the total weight of bean and radish for control are 798 gm/ plot and 875 gm/plot, respectively. The total weight of bean and radish was found to increase by 2.31 and 1.47 times, respectively in FW treated soil and 1.95 times and 1.35 times, respectively for CW during water stress condition. For



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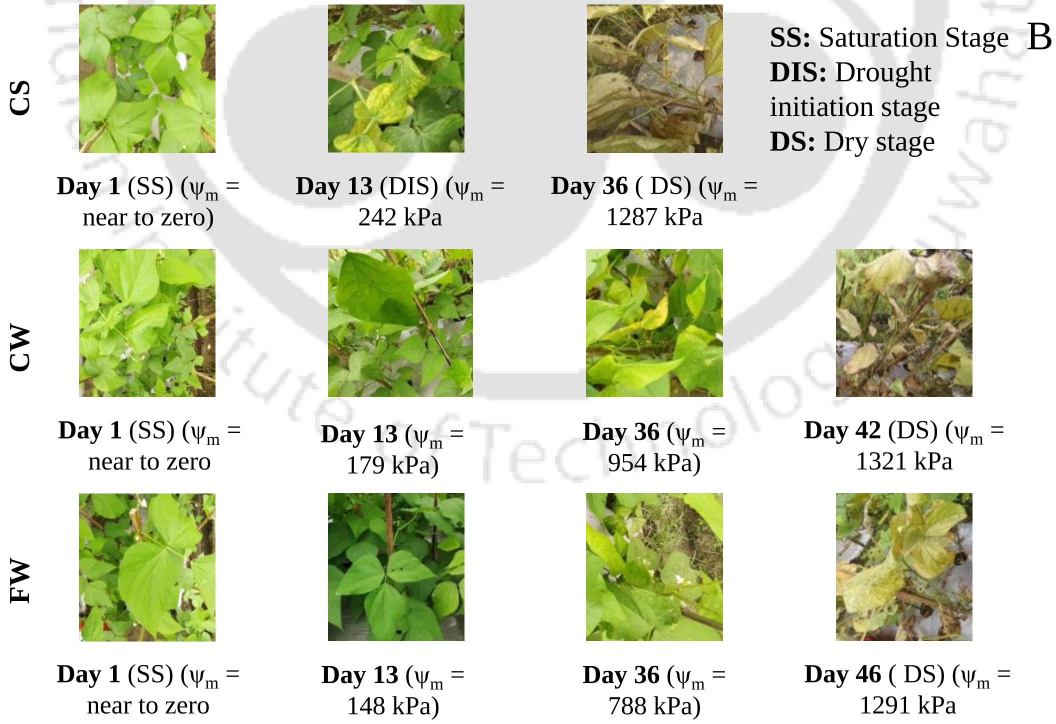
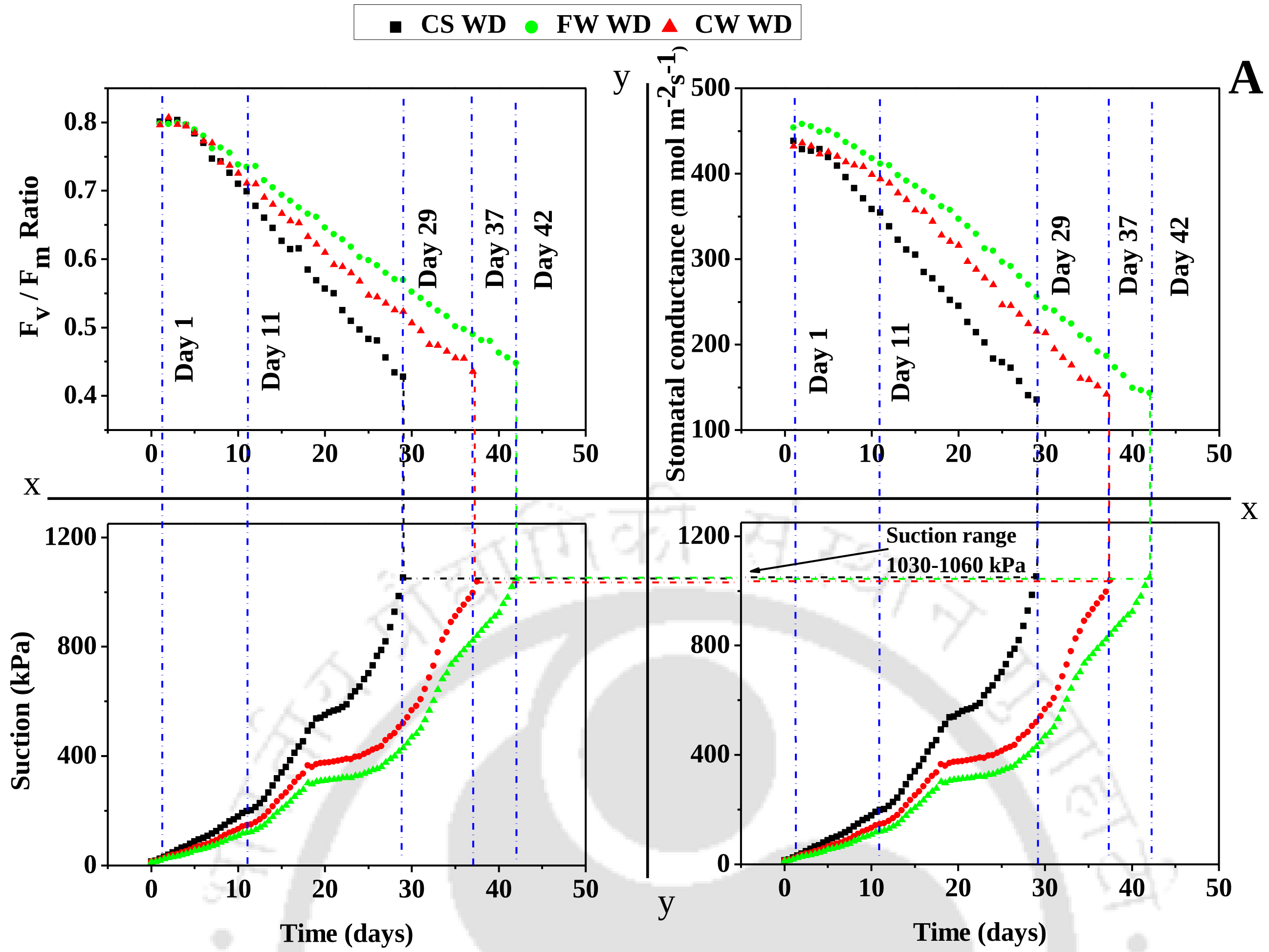


Figure 5.15: Drought response (saturated to dry stage) of beans presented by (A) Variation of SC, PY and suction with time for determining the wilting and (B) Visual depictions of leaf at different stages of drought



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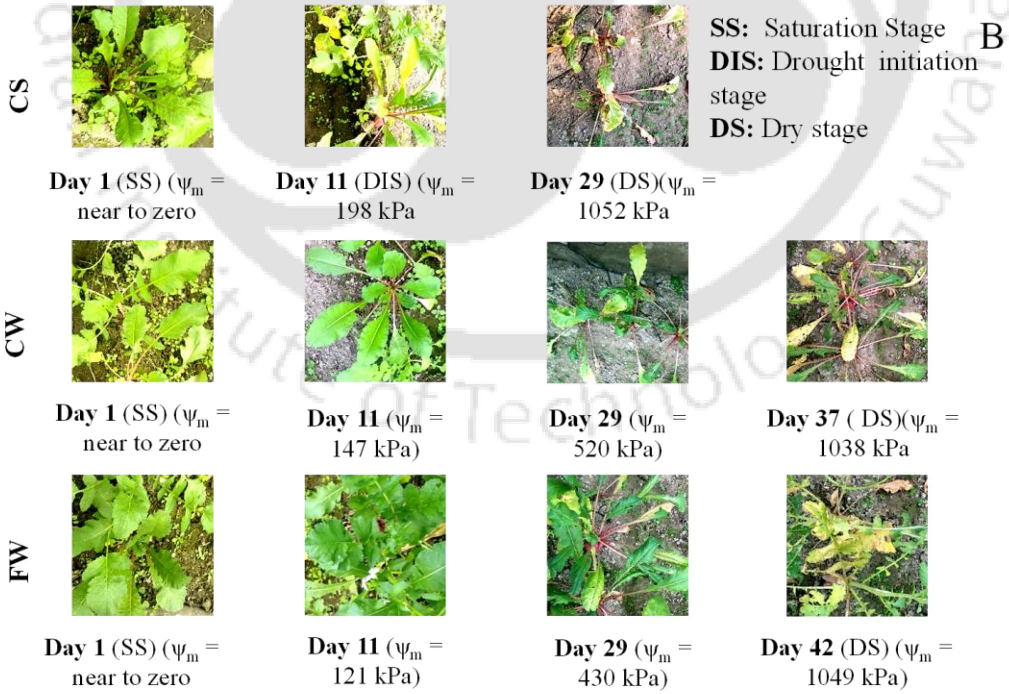


Figure 5.16: Drought response (saturated to dry stage) of Radish presented by (A) Variation of SC, PY and suction with time for determining the wilting and (B) Visual depictions of leaf at different stages of drought.

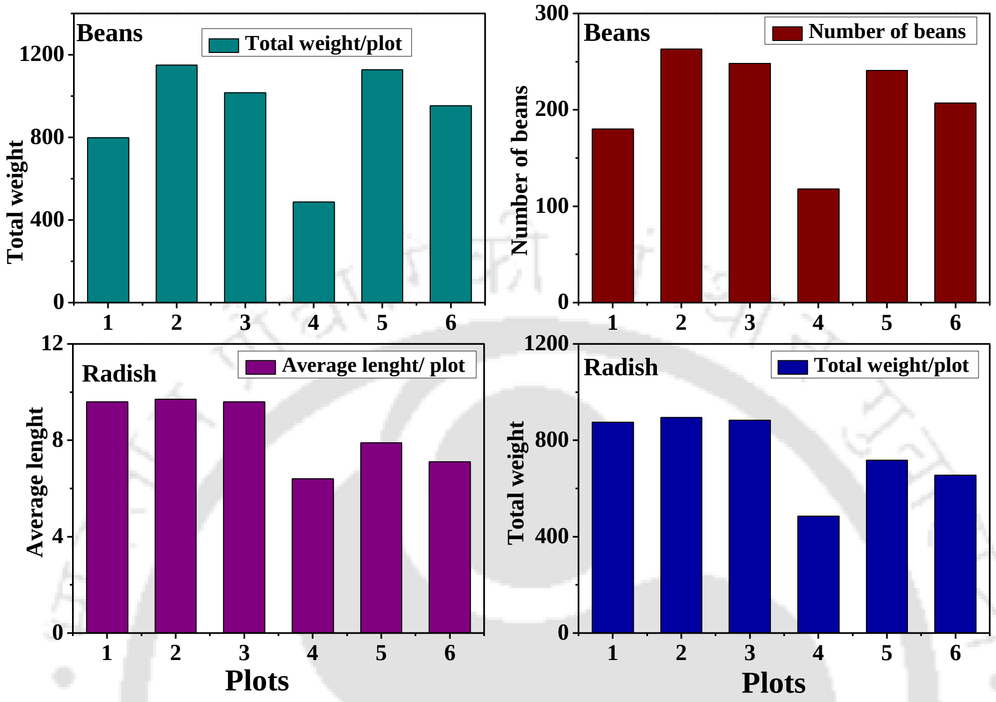
Table 5.6: Interpretation of suction value at drought initiation based on SC, PY and visual images

	Suction value (kPa) at drought initiation corresponding to			Suction range	Overall suction range
	SC	F_v/F_m ratio	Visual image		
Beans					
CS WD	250	230	242	230-250	**215-250 kPa**
CW WD	220	215	246	215-246	
FW WD	235	240	238	235-240	
Radish					
CS WD	200	210	198	195-210	**175-211 kPa**
CW WD	175	195	211	175-211	
FW WD	190	180	208	185-208	

Table 5.7: Interpretation of suction value at dry stage (wilting) based on SC, PY and visual images

	Suction value (kPa) at dry stage (wilting) corresponds to			Suction range	Overall suction range
	SC	F_v/F_m ratio	Visual image		
Beans					
CS WD	1280	1300	1287	1280- 1300	**1280-1330 kPa**
CW WD	1295	1330	1321	1295-1330	
FW WD	1285	1315	1291	1285- 1315	
Radish					
CS WD	1060	1050	1052	1050-1060	**1030-1060 kPa**
CW WD	1035	1030	1038	1030-138	
FW WD	1050	1055	1049	1049-1055	

well-watered condition, the total weight was found to increase by 1.44 times and 1.28 times for FW and CW, respectively for beans. While for radish, it is 1.02 times more in both FW and CW than control. The length of bean and radish were increased with WAPs as shown in **Figure 5.17**. The productivity of bean plants was 98% in FW and 94% in CW for bean under water deficit condition compared to well-watered condition. However, it was only 61% in control. Likewise, for radish it was 81 % in FW, 75 % in CW and 56% in control compared to wet-watered condition. The results indicate that WAP amended soil could withstand water stress without compromising crop yield. These results indicate that the WAP application can increase water availability in the soil matrix than control during water stress conditions. Being an agrarian economy, agriculture is the largest consumer of water, accounting for almost 89% of the total water consumption in India. These promising results indicate that the addition of WAP can help to minimize water use for irrigation and at same time promote crop yield during water deficit condition.



Plot 1: CS WW, Plot 2: FW WW, Plot 3: CW WW
Plot 4: CS WD, Plot 5: FW WD, Plot 6: CW WD

Figure 5.17: Effect of water-absorbing polymer (WAP) on yield parameters during water deficit condition

5.3.2.2) Tomato species

5.3.2.2.1) General

The total plot area was divided into three uniform sizes of subplots with an area of 4 m^2 (length and width of 2 m each). In the first subplot, the control soil with no WAP amendment was used. In the last two subplots, the dry soil was mixed with dry WAP (both CW and FW) up to 30 cm depth, which is the minimum root length for tomato plants (Guo et al., 2008). Two different inorganic fertilizers (urea and DAP) and one organic fertilizer (cow manure) were applied in equal quantities to each subplot. The application rate of inorganic fertilizers and organic fertilizer were kept as 100 kg/ha and 1000 kg/ha, respectively. The applied fertilizer quantity was decided based on the past field studies, the application rate of inorganic and organic fertilizer is 40 gm and 400 gm respectively in each subplot (Kumar et al., 2014; Alhasan et al., 2020). After germination, plants have developed up to vegetative stage (near to reach flowering stage) under well water condition. After reaching the flowering stage, plants have been subject to continue water stress condition up to permanent wilting point. Initially, irrigation performed before the soil suction was kept within a range of 100 kPa in an effort to maintain well water condition. After development of plant (reaches vegetative stage), irrigation was stopped causing all plots to be subjected to continued water stress until the plant reaches the permanent wilting.

5.3.2.2.2) Influence of WAP on SWCC

Figure 5.18 shows the influence of different WAPs (CW and FW) on SWCC of the field soil under well-watered conditions and continued water stress conditions. It may be noted that the continuous field monitoring of soil suction (ψ and water content (θ) were started from the vegetative stage of plant growth (i.e., after development and growth of plant roots and leaves). The plants were not subjected to drought conditions immediately after the vegetation stage. Instead, there were two cycles of well-watered conditions, where soil ψ remains below 100 kPa. This was done to ensure proper growth of plant roots and leaf development. The SWCC of control soil and WAP amended soils with the two cycles of well-watered conditions was followed up by one cycle of drought condition is presented in **Figure 5.18(a)**. The results indicate an improvement in water retention of soil with the WAP amendment. Higher retention can be observed in the lower suction range ($\psi < 100$ kPa) as compared to the higher suction range ($\psi > 100$ kPa) because of the modification of soil-pore structure with WAP addition. It is likely contributed by the capillary pore water (capillary effect) which is dependent on particle and pore size of soil (Lu and Likos, 2004). With the application of WAP, the unoccupied pore spaces are filled by WAP that absorbs water (indicated in **Figure 5.18(a)).** Similar trends were discussed in the literature (Wei and Durian 2013; Rahmati et al., 2019). With the application of WAP, the soil-polymer interaction takes place on the surface of soil particles thereby enhancing the specific surface area (SSA) which helps to retain water in the form of thin films on the surface of the soil. The above two mechanisms also enhance water retention of soil in the higher suction values ($\psi > 100$ kPa) (Lu and Khorshidi, 2015; Saha et al., 2020b). Among the WAP amended soils with plant, the SWCC of FW amended soil was found to be higher than CW amended soil due to presence of the aluminate material in the FW. The SWCC in **Figure 5.18(b)** shows the influence of vegetation and plant roots on SWCC of control and WAP amended soils under continued water stress conditions. It can be observed that the SWCC was slightly increased in vegetated soils for all the treatment (including WAP amended soils).

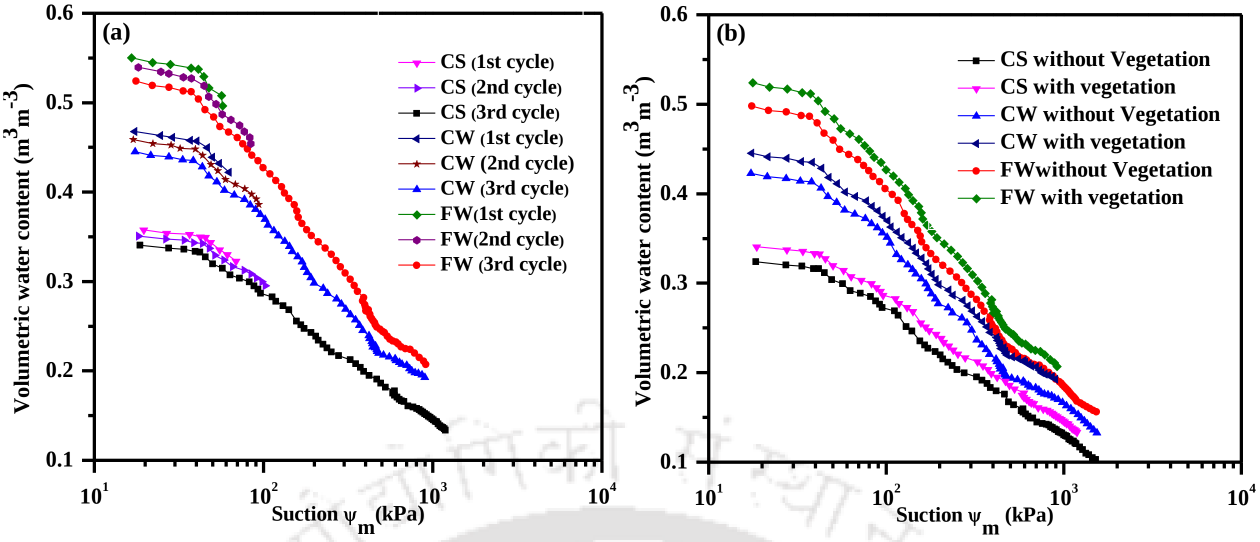


Figure 5.18. SWCC of control soil and WAP amended soils; quantifying effects of (a) WAPs and (b) vegetation on SWCC of the used soils for well-watered conditions (1st and 2nd cycle) and drought condition (3rd cycle)

The increment in SWCC for the whole range of ψ values remains almost similar in all the treatments with vegetation. It can be observed from Figure that root has also influenced the water retention behavior of soil for both with and without WAP amended soil. This is likely due to difference in root biomass and presence of root in the soil pore space as also observed in previous studies (Leung et al., 2015 and Ng et al., 2016). These studies showed that due to presence of root in the soil matrix, the air entry value (AEV) increased. The SWCC of control soil and WAP amended soils (both CW and FW) were further used to calculate saturated water content, field capacity, permanent wilting point and plant available water content. The influence of both WAPs on SWC, PWP and PAWC of soil with and without vegetation are presented in **Figure 5.19**. Practically, there is not much difference in SWC (less than 5% for all the treatments) and PWP (less than 10% for all the treatments) for soil with and without vegetation for all treatments. The WAP amended soils have shown higher SWC, PWP, and PAWC than control soil for both WAPs (Saha et al., 2020b). The improvement in the SWCC parameters were higher in WAP amended soils than control soil. The improvement in PAWC for CW amended soils and FW amended soils were 1.33 times and 1.68 times, respectively, as compared to the control soil. Similarly, SWC was increased by 1.25 times and 1.34 times in CW and FW amended soils, respectively as compared to control soil. In addition, PWP has also increment by 1.28 times and 1.33 times in CW and FW amended soil, respectively. This clearly indicates that the WAP addition

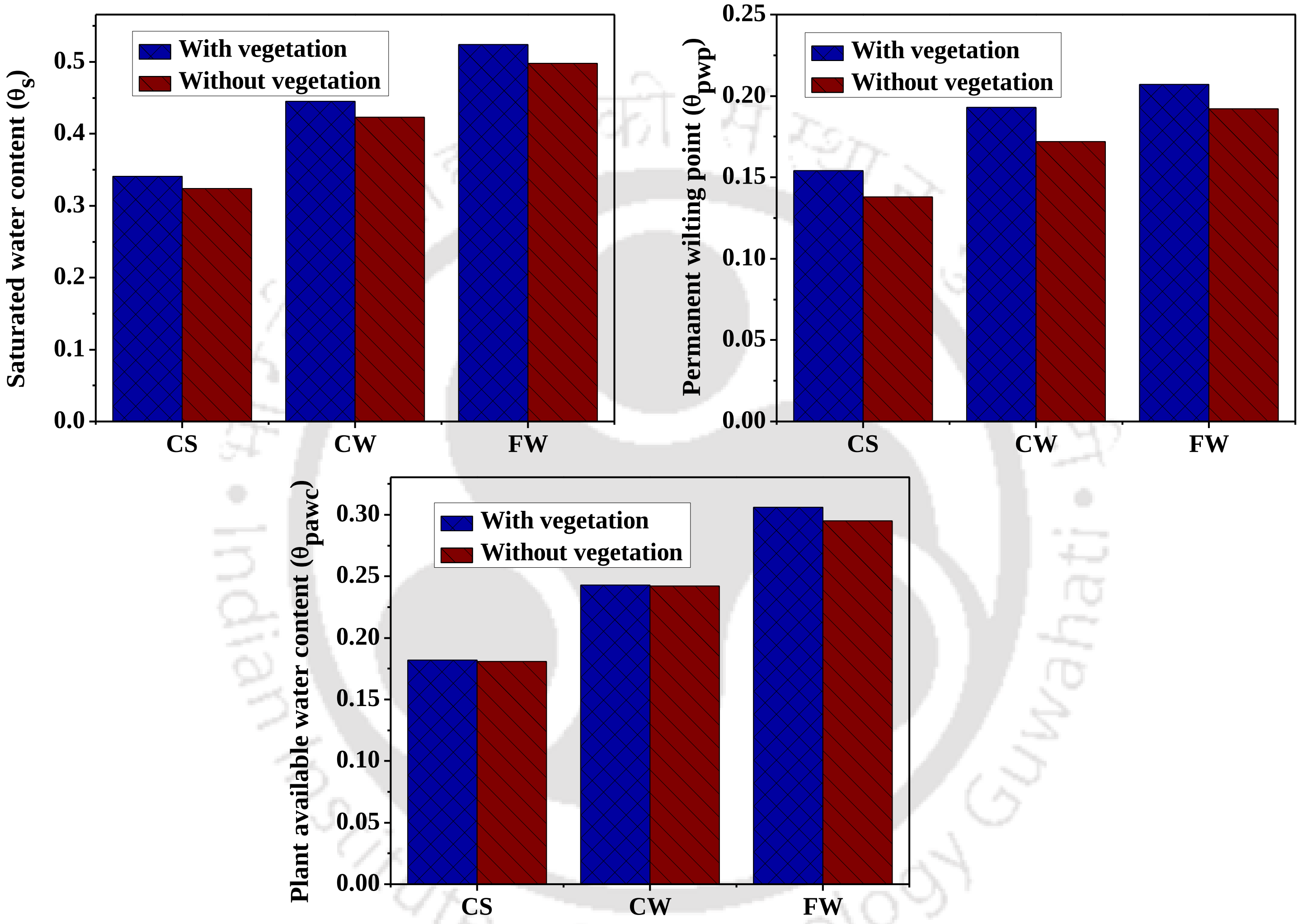


Figure 5.19. Saturated water content, permanent wilting point and plant available water content of WAP amended soils with and without vegetation

has increased the soil-water storage, which can function as a supplementary micro storage reservoir under continued water stress condition. However, the information reported above is partial if the plant response under continued water stress is not quantified. The following section deals with the plant response quantified in terms of SC and PY under continued water stress condition.

5.3.2.2.3) Influence of WAP on drought resistance of tomato species

5.3.2.2.3.1) Stomatal conductance and photosynthetic yield

The diurnal SC variation for different treatments is presented in **Figure 5.20 (a)**. The results show insignificant difference in SC value between the control soil and WAP amended soil. This means that the water loss from leaves is almost the same in all treatments under well-watered condition, indicated by the diurnal variation (**Figure 5.20 (a)**). Callaghan et al. (1989) reported that no significant difference in SC with WAP amended soil during diurnal observation of eucalyptus plants under well-watered conditions. Moreover, the SC values vary from 335 mmol m^{-2} s^{-1} to 658 mmol m^{-2} s^{-1} in daytime for well-watered condition in tomato species, and favourable plant growth with maximum SC value at 12:30 PM. This is due to the higher light intensity and full opening of stomata occurring at mid-day (around 12:00 pm to 1:00 pm).

The peak value of SC measured at 12:30 PM during drought cycle is presented as a function of time to understand the efficacy of WAP treatment. Generally, stomata closure occurs in the leaves under insufficient water availability. It can be observed that, the SC values decreased for the treatments under continued water stress conditions which might be due to the closure of stomata in the leaves according to the availability of water status. The rate of stomata closure occurs faster in the control soil than the WAP amended soil under continued water stress conditions. Arbona et al., (2005) has reported higher decrease in SC of citrus plants for control condition than WAP amendment. Stomata closure increases as time progresses until the plant reaches a permanent wilting point. The lowest value of SC recorded at wilting point (**Figure 5.20 (b)**) are 115 mmol m^{-2} s^{-1}, 190 mmol m^{-2} s^{-1}, 225 mmol m^{-2} s^{-1} for control soil, CW amended soil and FW- amended soil, respectively. The observations show that the addition of WAP has a significant positive effect on SC values. The increment of SC in the WAP amended soil endorse better plant health (Pill, 1984). The minimum value of SC is 115 mmol m^{-2} s^{-1} for tomato species from all treatments. From the Figure, at minimum SC, the leaf was almost dry (which means plant reaches near to permanent wilting point). Therefore, when SC reaches the range of 100-125 mmol m^{-2} s^{-1} it can be subject to a permanent wilting point for tomato species.

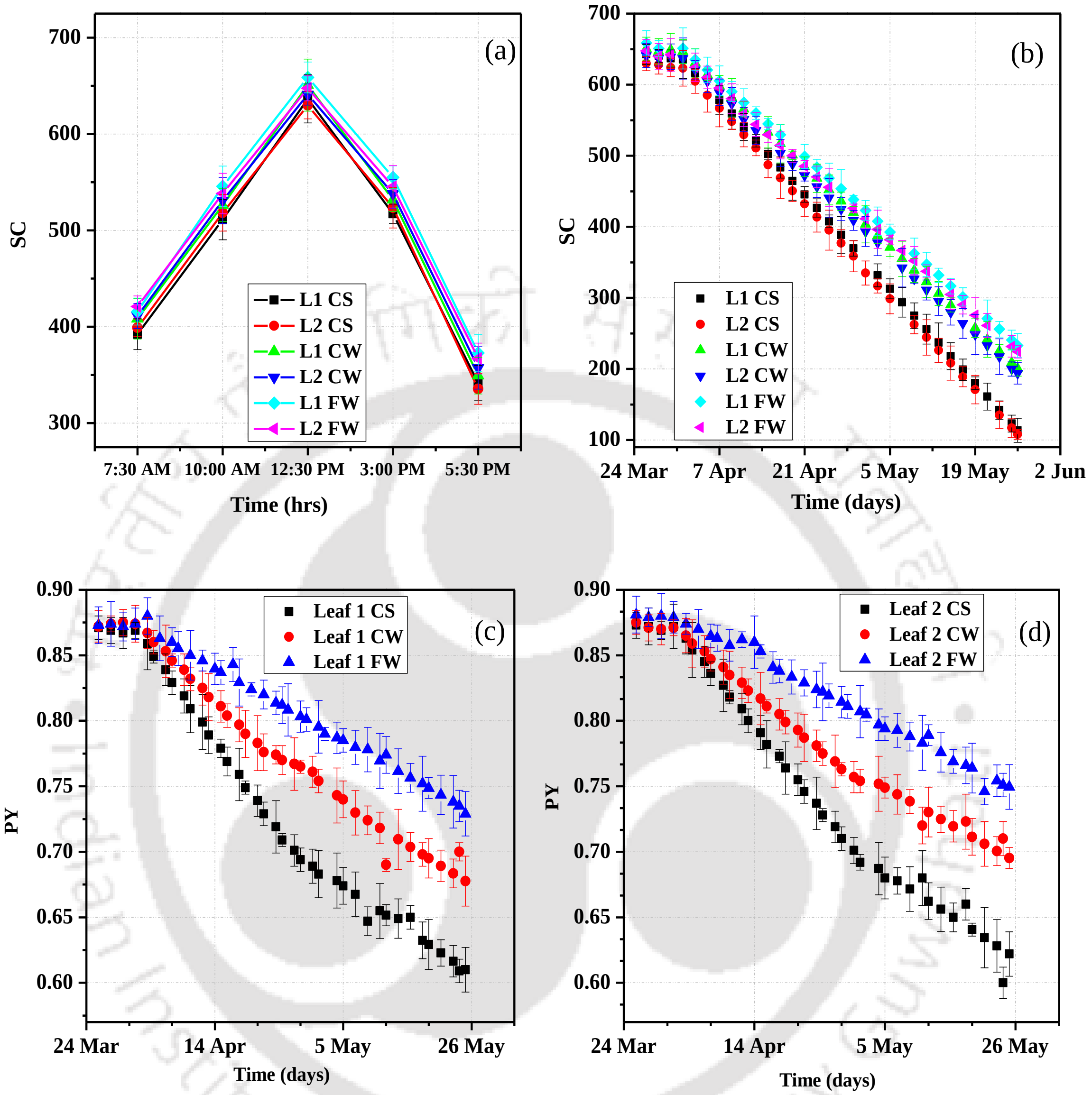


Figure 5.20 (a) Comparison of diurnal variations of SC, (b) variation of maximum value of stomatal conductance with time during drought period, and (c)-(d) variation of PY ratio of leaf 1 and leaf 2 with time during drought period

Maximum PY is another important plant parameter that is affected by water stress conditions (Galmes et al., 2007, Garg et al., 2020 Bordoloi et al., 2022). The maximum PY measured in terms of F_v/F_m is shown in **Figure 5.20 (c).** The PY remains almost similar for all the treatments in the initial stage when there is sufficient water available for plants. Under water-stressed conditions, PY decreased continuously for control soil and WAP amended soil until the plant reaches the wilting point (as shown in **Figures 5.20 (c) and**

(d). It can be observed that the PY decreases from 0.873 to 0.61 in control soil, 0.877 to 0.675 in CW amended soil, and 0.88 to 0.73 in FW amended soil under continued water stress conditions. These results are also supported by previous findings in the literature (Santos et al., 2013). Santos et al (2013) reported that the PY decreases from .83 to .6 of Jatropha curcas L plant species under continued water stress condition. The rate of decrement in PY follows the order of control soil > CW amended soil > FW amended soil. Therefore, the WAP amendment has improved the PY of the tomato plant and contributes towards better plant growth under continued water stress conditions.

It is explicit that soil water retention parameters and plant parameters are dependent on each other. Hence, this study explored the relationship between ψ and SC/ PY for the WAP amended soil under continued drought condition. These empirical relationships assist practitioners for categorizing and estimating the leaf transpiration rate with ψ during drought conditions for the WAP amended soil and control soil. **Figures 5.21 (a-b)** present the variation of peak SC value with the ψ under continued water stress condition. The SC was found to be maximum at fully saturated conditions and remains almost constant up to a ψ value of 50 kPa. The SC decreases with an increasing ψ as the leaves are subjected to drought stress (Munemasa et al., 2015; Garg et al, 2021). With an increasing ψ, stomata transmit signals to abscisic acid (plant hormone) which causes partial or complete closure of stomata followed by changes in pH and concentration of Ca^{2+}, Cl^{-} and K^{+} (Wilkinson and Davies, 1997; Tipple and Pagani, 2007). It can be further observed from **Figures 5.21(a-b)** that the SC - ψ variation results in a unique relationship for control soil and WAP amended soil. This indicates that the SC – ψ variation is primarily governed by plant species, rather than the type of WAP.

Figure 5.21 (c-d) presents the relationship between photosynthetic yield parameter (PY) and ψ for control soil and WAP amended soils. It can be observed that the maximum value of PY was observed in the saturated condition and ψ value below 50 kPa. PY gradually decreased with the increasing ψ range, and the rate of decrement was found higher in control soil as compared to WAP amended soil. It was reported that the soil texture in terms of pore size distribution would influence the plant photosynthesis response due to water uptake in the photosystem- II mechanism under continued drought conditions (Garg et al., 2021). Similarly, water uptake capacity is likely influenced by the presence of WAP, that would reduce the pore size distribution of the control soil and result in higher plant available water content. This might explain the reason for the observed maximum PY

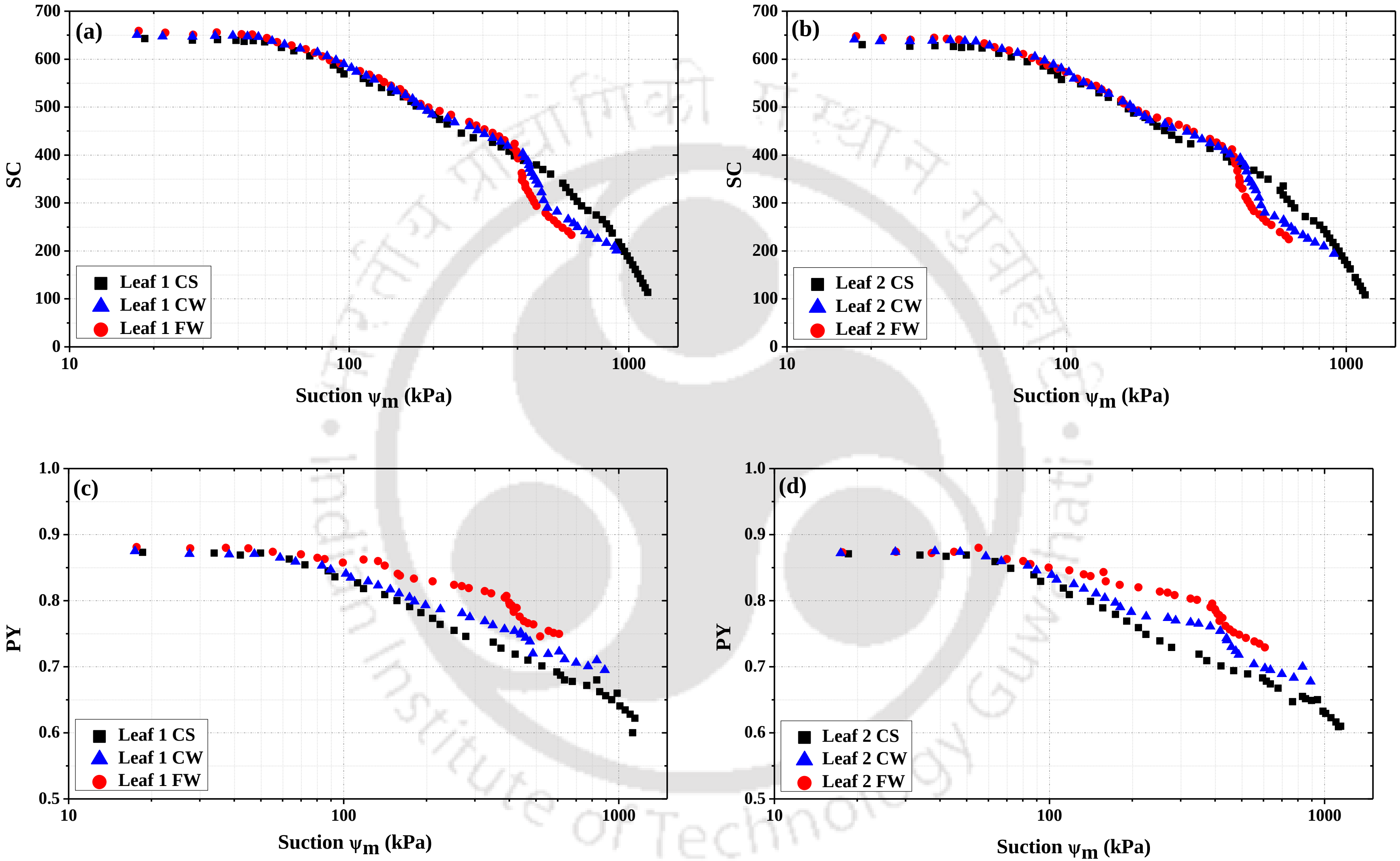
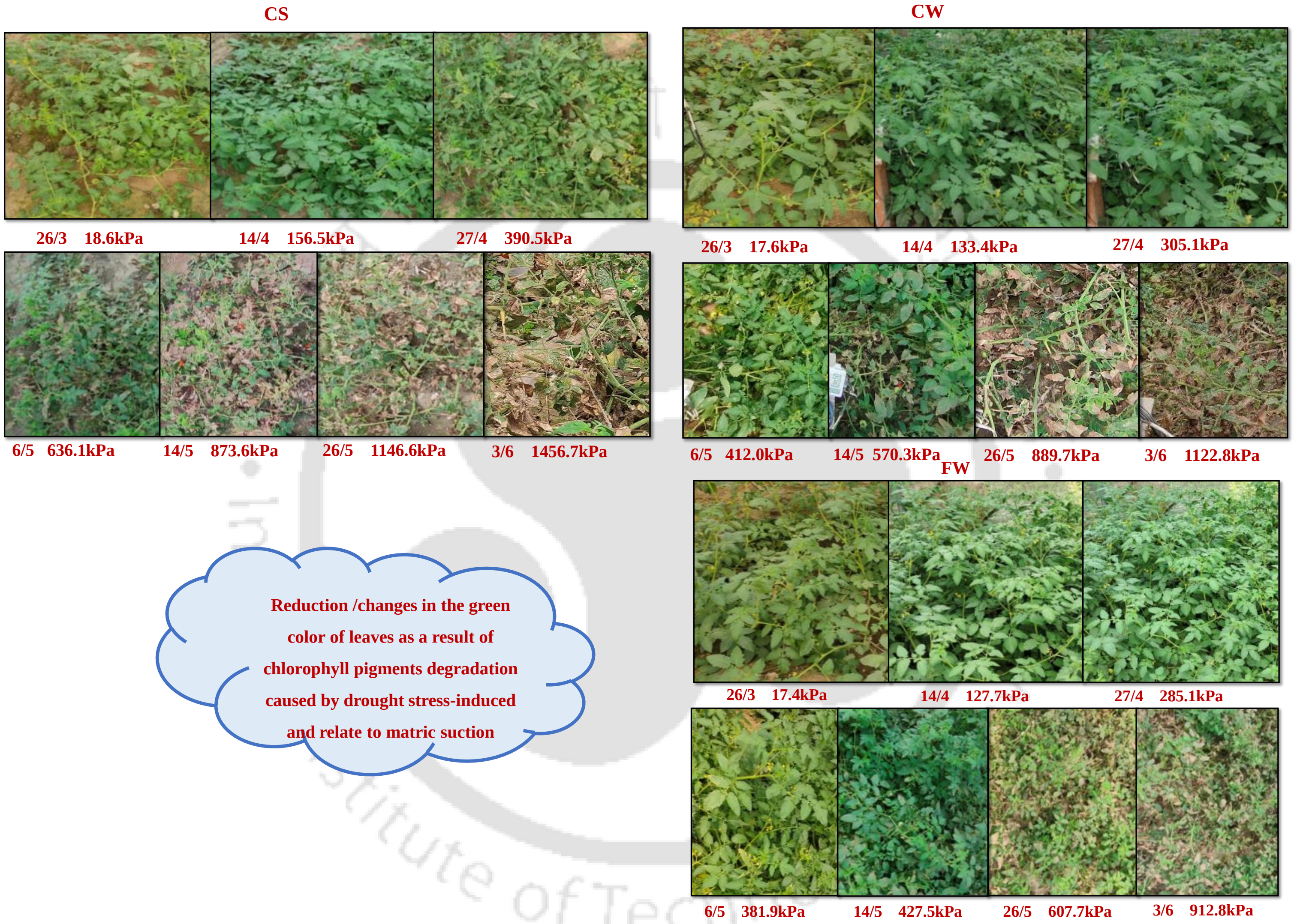


Figure 5.21 Variation of stomatal conductance (SC) (a-b) and photosynthetic yield (PY) (c-d) with suction for Leaf 1 and Leaf 2.



Reduction /changes in the green color of leaves as a result of chlorophyll pigments degradation caused by drought stress-induced and relate to matric suction

Figure 5.22: Leaf health status at different soil suction during continued drought state for tested soils

in WAP amended soils as compared to the control soil. Unlike SC, the PY- ψ relationship is dependent on both WAP type and plant species. Bordoloi et al., 2022 reported the new terminology "tipping suction" for suction values corresponding to PY values. It presents the plant survivorship shift to permanent wilting which would be minimum moisture for plant survival

5.3.2.2.3.2) Influence of WAP on the leaf health

A total of seven photographs, as shown in **Figure 5.22**, were selected to demonstrate the changes in leaf health under continued water stress condition and ψ for control soil and WAP amended soil. The monitoring period ranged from 26-March, 2021 to 3rd June, 2021, which represents the vegetative stage to wilting stage. For the control soil, the plant likely reached the wilting point by 14th May 2021 corresponding to a ψ of 873.6 kPa. On the other hand, plant grown in CW and FW amended soil exhibited dry and damaged leaves (signs of wilting) by 26th May, 2021 and 3rd June, 2021 at similar ψ ranges of 889.7 kPa and 912 kPa, respectively. The results of percentage damage of leaves in WAP amended soil and control soil are presented in **table 5.8**. The obtained results showed that the maximum leaf damage occurs in the control soil than WAP amended soil. The damaged leaf area follows the order FW amended soil (40.67 %) < CW amended soil (51.8 %) < control soil (65.25 %). These results clearly suggest that the addition of WAP has prolonged the leaf damage of tomato plant, and the performance of FW is better than CW in terms of preventing leaf damage. Gilani et al., (2022) reported that more leaf area is present in WAP amended soil than control soil under continued water stress condition.

5.3.2.2.3.3) Influence of WAP on plant survival

The variation of ψ with time at different stages of plant growth under well-watered condition and continued drought condition was continuously monitored using the TERSOS21 sensor and presented in **Figure 5.23**. Under well-watered condition at ψ range within 100 kPa, the ψ in control soil and WAP amended soil was observed to be practically same. Under drought condition, slope of ψ -time plot was higher in control soil than WAP amended soil. Most of the previous studies considered a ψ value of 1500 kPa to estimate the plant wilting time (also considered as plant survival time) for all plant species and soil texture (Feddes, 1982; Saxton and Rawls, 2006; Garg et al., 2020). However, the present study observed that the tomato plant can survive only up to the ψ values ranging between 860 and 920 kPa considering all the treatments (with and without WAP). From this, it can

Table 5.8: Result of damaged leaf area by ImageJ analysis

Treatments	Image consider at different stage	Total area of image (pixel)	Percentage area of green leaf	Percentage area of damaged leaf during drought
CS	Vegetative stage (a)	275600	91.27	65.25
	Drought stage (b)	275600	26.02	
CW	Vegetative stage (a)	275600	93.35	51.8
	Drought stage (b)	275600	41.55	
FW	Vegetative stage (a)	275600	90.79	40.67
	Drought stage (b)	275600	50.12	

be concluded that for wilting point for the tomato species corresponds to the ψ value of 900 kPa for silt loam. For precise irrigation, it requires threshold suction values that will help to facilitate the irrigation scheduling. The present study gives threshold suction at 900 kPa of tomato species for silt loam which results in optimum irrigation or increases to chance of plant survival. It may vary that the plant wilting time depends on various parameters such as plant species, climate conditions, and soil texture (Shafroth et al., 2000; McDowell et al., 2008). Additionally, the plant survival time was confirmed by visual inspection for all the WAP amended soils during continued water stress conditions and reported in **Figure 5.23**. It can be observed that plant wilting time increases with the addition of WAP. The order of increasing plant wilting time is control soil (1152 hrs.) < CW amended soil (1440 hrs.) < FW amended soil (1632 hrs.) from the beginning of 3rd cycle (imposed drought). The PWT was found to be increased by 1.41 times and 1.25 times for FW amended soil and CW amended soil, respectively, as compared to the control soil (Saha et al., 2020a; Gehring and Lewis, 1980). The observations from the Figure suggest that the WAP amendment can help to reduce the irrigation frequency (i.e., time intervals between two successive irrigations by storing more water in the soil-WAP matrix) and prolong the tomato plant survival under continued drought conditions. A similar observation was reported in Saha et al. (2020a) through laboratory investigations of WAP amendment soil without vegetation. The present study validates those observations for a vegetated soil under field conditions.

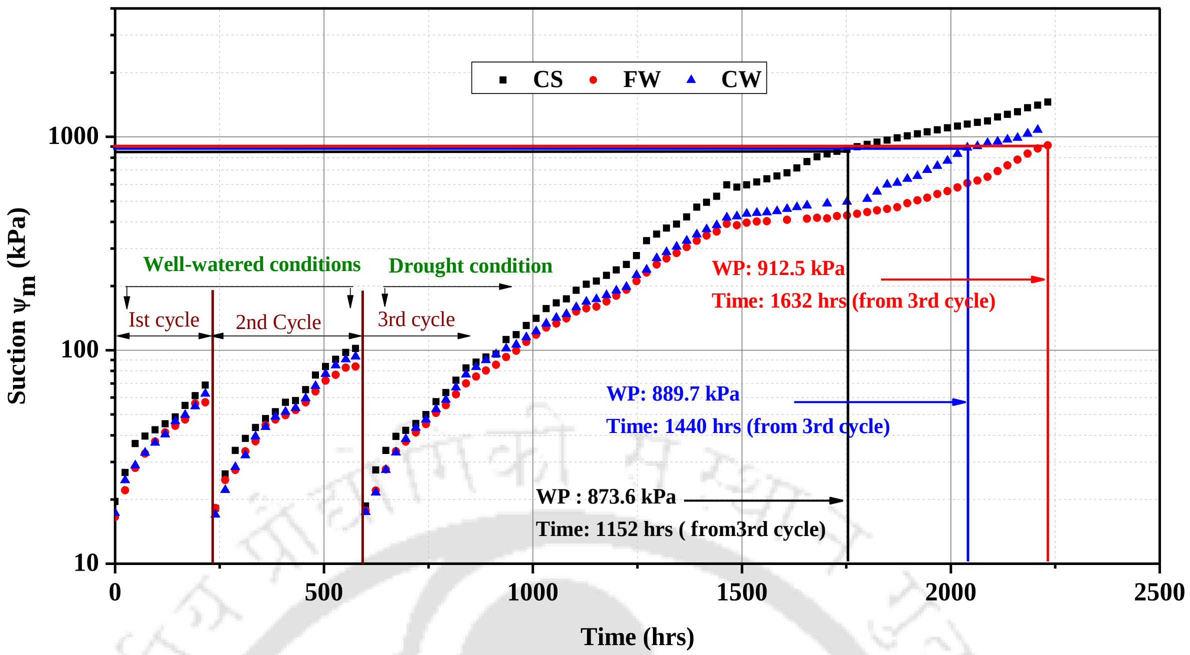


Figure 5.23 Suction variation with time for control soil and WAP amended soils

5.3.2.2.4) Influence of WAP on plant yield parameters

Figure 5.24 present the results of yield parameters in WAP amended soil and control soil. Both WAPs (CW and FW) have improved yields parameters than control soil under continued water stress conditions. The total weight of fruits and diameters are 3393 g and 3.82 cm for the control soil (Afzal et al., 2015). The effect of FW amendment on the yield parameters could be observed based on the increase in the total number of fruits (1.82 times), CW amended soil, respectively. Similarly, shoot dry biomass was increased by 2.2 weight of fruits (2.06 times), volume of fruits (2.01 times), and average diameter of fruit (0.94 times) as compared to the control soil. On the other hand, the application of CW has increased the total number, weight, volume, and average diameter of fruits by 1.49, 1.71, 1.62, and 0.96 times respectively. The results indicate that use of FW can yield much more tomato than the control soil. **Figure 5.25** presents that the influence of both WAPs (FW and CW) on the plant shoot biomass. The minimum shoot fresh biomass was observed in the control soil, which was increased by 2.1 times and 1.9 times in FW amended soil and times and 2 times with FW and CW amendment. Showemimo and Olarewaju (2007) have reported that drought is an drought stress factor that reduces plant growth and yield parameters. It is clearly understood from **Figures 5.24 and 5.25** that plant growth and yield parameters are increased with WAP amendment in the soil. This study indicates that the yield parameters of tomato is positively impacted by the addition of WAP under continued drought condition. The study also endorses the benefit of laboratory synthesized FW for improving plant growth. It is clear from this study that both WAPs were instrumental in storing water and adequately releasing it into the soil under continued drought condition.

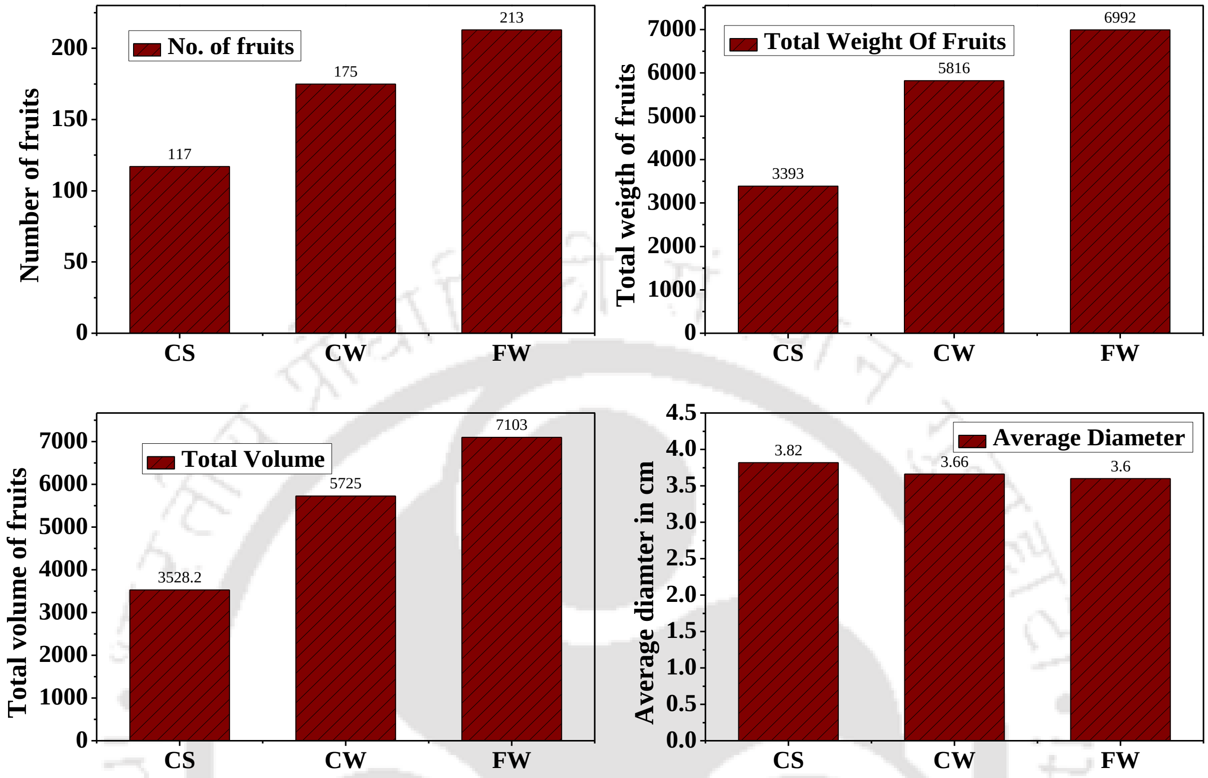


Figure 5.24: Plant yield parameters effect of CW and FW at the end of drought application.

5.4) Conclusions

5.4.1) For laboratory condition

This study defined two parameters, drought initiation point (DIP) and final drought point (FDP) for unravelling the drought progression in plants subjected to water stress. The plant response to drought was determined by measuring stomatal conductance (SC) and photosynthetic yield (PY). The normalized SC (NSC), PY and soil suction (SS) corresponding to DIP and FDP was determined for two plant type (beans and radish) grown in silt loam and silt. The soils were subjected to various amendments by adding organic fertilizer, commercially available water absorbing polymer (WAP) and in-house synthesized fly ash WAP.

- For both the plant type grown in both the soils, the increasing order of saturated water content (SWC), plant available water content (PAWC), and permanent wilting time (PWT) was consistently CS WD < CSO WD < CW WD < CWO WD < FW WD < FWO WD.

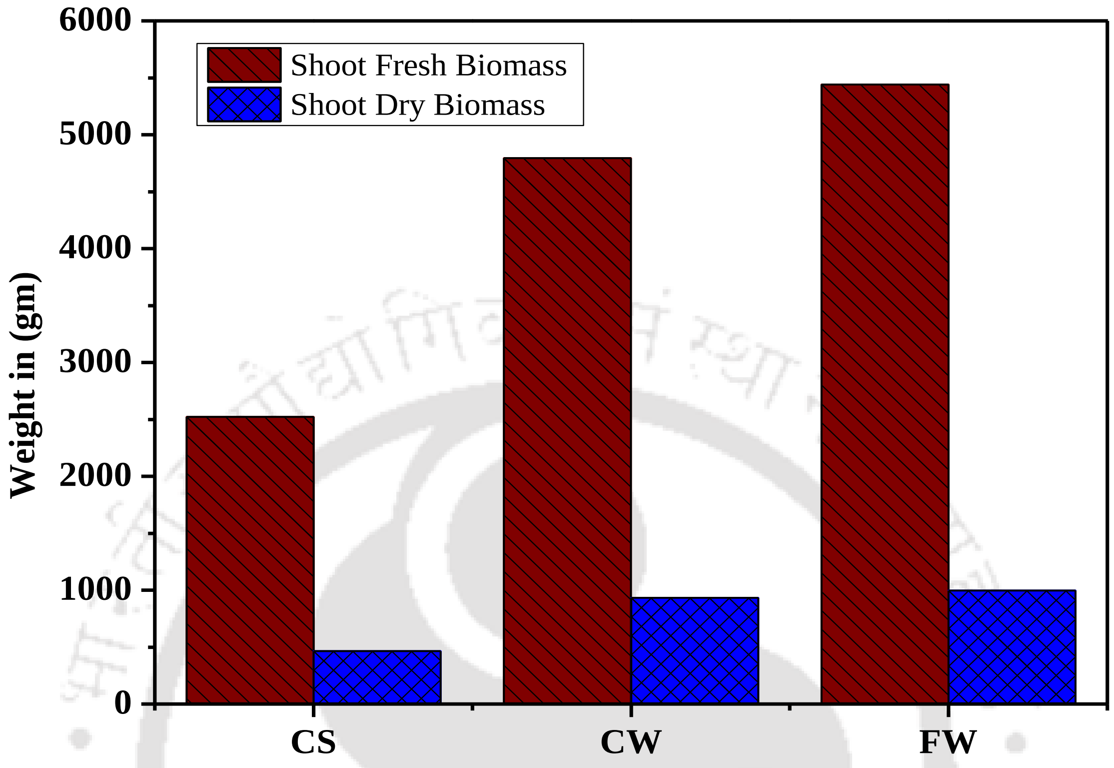


Figure 5.25: Plant biomass of tested plants

- In the presence of WAP, the PAWC improvement is approximately 2 times in silt loam, and 1.5 times in silt for both the species.
- The PWT is improved by 1.35 times for CW and 1.5 times for FW in both the species grown in silt loam, whereas 1.5 times for CW and 1.7 times for FW for both the species in silt.
- Under water-deficit condition, it is demonstrated from this study that SC and PY values at the beginning and end of drought are influenced by plant type, soil type, organic fertilizer, and WAP amendment. In general, the variation of SC and PY followed the order CS < CSO < CW < CWO < FW < FWO.
- The overall variation of SS-DIP and SS-FDP is in the range 125-229 kPa and 940-1310 kPa, respectively considering all the measurement combinations considered (soil type, plant type and soil amednements).
- The study demonstrated the possibility of plant specific linear relationship between SS, NSC and PY at FDP with its respective values at DIP. The SS-FDP was more specifically dependent on plant species than SS-DIP. Similarly, PY-FDP was

distinctly different for both the species compared to NSC-FDP with beans showing higher values than radish.

- The observation from this study brings out the fact that soil type (silt loam and silt) has negligible influence on drought related parameters. The plant type (beans and radish) had a pivotal role in the determination of drought related parameters. The various soil amendments considered in this study had negligible influence on the drought related parameters

Based on this study, the range of parameters related to drought progression was determined. It was noted that NSC-DIP, NSC-FDP and PY-DIP exhibited a unique range considering all soil type, plant type and soil amendments. For parameters, SS-DIP, SS-FDP and PY-FDP the range was dictated by the plant type.

5.4.2) For field condition

5.4.2.1) Beans and radish

This study investigates the wilting pattern of crop species, bean and radish, in silt loam. This was accomplished by incorporating analysis of plant physiological parameters, soil water retention behaviour, and visual interpretation. This study investigated the dynamics of drought by capturing the variation of stomatal conductance (SC) and photosynthetic yield (PY) with soil suction, which was further used to determine permanent wilting point (PWP). Following is the summary of findings from this study.

- WAP has improved the water retention by storing water within the pore volume of soil matrix. FW has higher water retention than CW due to aluminosilicate material’s contribution.
- The rate of decrease in SC and PY was found to be less in WAP amended soil, which indicates less water stress on plants under water-deficit condition.
- The drought effect (drought initiation point) initiated at soil suction values between 215-250 kPa for bean and 175-211 kPa for radish.
- The quantification of PWP based on SC and PY indicated wilting suction of 1300 kPa and 1050 kPa for bean and radish, respectively.
- The addition of FW enhances yield by 2.31 and 1.47 times for bean and radish, respectively whereas for CW the increase in yield is 1.95 and 1.35 times.

The above findings demonstrate that the in-house developed FW has high potential to reduce irrigation frequency/ water requirements during dry spells without sacrificing crop output. Such an understanding facilitates alternate method for crop growth in arid and semi-arid regions during water deficit condition, thereby paving way for food security.

5.4.2.2) Tomato

Both CW and FW contributed positively on plant growth under continued water stress condition. It is explicit that the WAP could store water and release it to the soil during drying, which could be effectively used by the tomato plant. The following conclusions are drawn from this study:

- The SWCC of FW amended soil was higher than CW amended soil and control soil.
- WAP amended soil exhibited higher saturated water content, permanent wilting time, and PAWC as compared to control soil, with FW exhibiting a better performance.
- SC and PY indicated that the rate of decrement of both the parameters was more in the control soil than WAP amended soil.
- Addition of WAP was instrumental in minimizing leaf damage, with FW performing better than CW.
- The permanent wilting time has increased by 1.41 times and 1.25 times for FW amended soil and CW amended soil, respectively, as compared to the control soil.
- WAP amendment has increased the crop yield- total number of fruits (1.82 and 1.49 times), total weight of fruits (2.06 and 1.71 times), shoot fresh biomass (2.1 and 1.9 times) for FW and CW respectively, as compared to the control soil.

Based on these conclusions, it is quite evident that WAP application can significantly reduce the irrigation frequency and irrigation water requirement without compromising the crop yield, which is crucial in arid and semi-arid regions of the world and during the drought spell.

Chapter 6

Impact of WAP on the microbial community of unsaturated soil

6.1) Introduction

Soil play a crucial role in agriculture as it affects nutrient cycle, water availability, and plant oxygen, all of which are vital for plant growth and development (Swift et al., 1998). To ensure food security for the expanding population under the challenges of climate change, and achieve sustainability goals (sustainability goals no., 2, 15, and 17), it is imperative to focus on soil conservation and management. The properties and characteristics of soil, such as soil type, texture, and microbial community influence soil fertility, stability, and nutrient cycle (Chapman et al., 2006; Dai et al., 2023). The microbial community plays a vital role in maintaining soil health by supporting nutrient cycle, decomposing organic matter, and enhancing plant growth and productivity (Kibblewhite et al., 2008). Furthermore, it contributes to the development of healthy roots, which are crucial for plant well-being. However, soil health is adversely affected by water scarcity, leading to mineral depletion and disruptions in the microbial community (Hueso et al., 2012). Water scarcity, considered a natural disaster, impacts multiple sectors including agriculture, urban green planning, and green infrastructure. Approximately 40% of agricultural lands worldwide suffer from water stress annually, and mitigating such challenges is of utmost importance.

Researchers are exploring various strategies and methodologies to minimize the impact of drought and water stress condition. One potential approach to alleviate the detrimental effects of drought stress/ water stress is soil amendment like biochar, water-absorbing polymers (WAPs), and gypsum. Biochar is derived from the pyrolysis of biomass and has shown promising results in enhancing soil structure, water retention, and nutrient availability (Xu et al., 2012). The WAP are synthesized materials capable of absorbing significant amount of water, that can release water into the soil during water stress in plants (Saha et al., 2020c). Gypsum, a mineral, is another amendment that can enhance soil structure, drainage, and reduce soil acidity (Hoeneck et al., 2007). The utilization of soil amendments to mitigate the impacts of drought stress is an emerging and promising strategy for improving crop yields and ensuring food security (Batool et al., 2015). However, further research is necessary to determine the potential benefits of soil amendments.

The WAP is a hydrophilic polymer with a three-dimensional network structure that has the ability to absorb and retain significant amounts of water. WAP has diverse applications in agriculture, horticulture, wastewater treatment, medicine delivery, and personal care products (Behera and Mahanwar, 2020). In agriculture, WAP is commonly used during drought conditions to help maintain soil moisture levels and promote plant growth. However, it is important to note that WAP may have an impact on the soil microbial community, given the fact that it is a synthesized material (Zhang and Guan, 2022). The soil microbial community consists of a diverse range of microorganisms, including bacteria, fungi, and viruses, that are complex in nature. Among these bacteria plays a vital role in different complex processes enhancing soil health (Dubey et al., 2019) or it can deteriorate the soil properties (Pahalvi et al., 2021). The bacteria perform various functions that are essential for plant growth and soil health, such as nutrient cycling, organic matter decomposition, and stress tolerance (Berendsen et al., 2012). They may also have antagonistic effects if they compete with plants for soil nutrients or act as one of the causative agents for plant diseases (Suganya et al., 2022). The existing literature has primarily focused on studying soil retention properties and plant parameters for WAP amended soil. Plant parameters, including phenotype (plant height, number of leaves, etc.) and physiological characteristics (stomatal conductance, photosynthetic yield, etc.), have been extensively investigated (Breuer et al., 2003; Garg et al., 2022). Numerous studies have demonstrated the significant improvement in plant growth and agricultural productivity due to WAP amendment (Kargar et al., 2017; Saha et al., 2020c).

It is important to recognize that the soil microbial community also plays a crucial role in plant growth and agricultural productivity. Therefore, the impact of WAP on the soil microbial community is an important consideration. Previous research has mainly focused on studying microbial communities in the context of water scarce environments (Fierer et al., 2003; Rolli et al., 2015). Some studies have explored the individual impacts of WAP, plants, and drought on microbial community (Dunfield and Germida, 2004; Bogati and Walczak, 2022; Li et al., 2014). However, there is a lack of comprehensive investigation into the combined influence of WAP amendment, plants, and drought conditions on the microbial community. Given the influence of soil bacteria on plant-microbe interactions and overall soil health, it is crucial to investigate whether the soil amendment like WAP has any undesirable effect under drought condition. The objective of this research is to systematically investigate the influence of WAP amendment on soil bacterial community in the presence of plant and subjected to drought condition. Studying the impact of WAP on microbial communities can shed light on its potential consequences for nutrient cycling, organic matter decomposition, and other essential soil processes.

In this study, the plant species *phaseolus vulgaris L.* (common bean) was grown in agricultural soil under control environment condition (greenhouse). Two different WAPs (commercial WAP and fly ash WAP) was used for soil amendment to study its impact on soil bacterial community. The three stages of bacterial analysis provide a comprehensive understanding on the changes in the microbial community with time (short-term), from initial condition to the end of drought stress cycle. The 16S rRNA gene sequencing was used to determine the taxonomic composition of the soil bacteria at the genus or species level, providing valuable information on the diversity and abundance of bacteria in the soil. Overall, this study has the potential to provide important information on the short-term impact of WAP amendment on the soil microbial community. The future scope of this work is the long-term impact of WAP on soil microbial community, including fungi and viruses.

6.2) Materials and Methodology

6.2.1) Site description and soil amendment

Soil for this study was collected from an agricultural field (AS) located in the Kamrup district of Assam, North-east India. The samples were taken from the root zone within a depth of 15 cm from the surface. Any visible plant residue, shoots, and debris were carefully examined and removed from the collected soil samples. The details characterization of the used soil is presented in Chapter 3. The soils were classified as silt loam (AS) according to the USDA classification (Simonson, 1962). Two different types of water-absorbing polymers (WAPs) were utilized in this study. The basic characterization of WAPs are discussed in **Chapter 3**. The *phaseolus vulgaris L.* (common bean) was chosen as the model plant species for this study.

6.2.2) Experimental details

The soil was prepared by dry mixing WAP equal to 2% of soil dry mass based on earlier studies (El-Asmar et al., 2017; Saha et al., 2020a). The plants were grown in the greenhouse under a controlled environment (temperature 25-28°C and humidity 50%). Initially, seeds were grown in a germination chamber, which provides an ideal atmosphere for better growth. The plants were transferred into pots after germination. Subsequently, plants were allowed to grow to the vegetative stage (near flowering or mature stage) under well-watered condition. After reaching the flowering stage, the plants were subjected to drought stress (no water was applied till the plant completely wilted). The samples were collected in three stages of the experiment- Stage 1: initial condition where the dry WAP was mixed and allowed to react with soil matrix for 10 days. At this stage, the influence of only WAP can be assessed. After collecting the samples at stage 1, then plants were transferred to the pots and allowed to grow up to the vegetative stage. In stage 2, the soil sample was collected after the plant reached the vegetative stage (the required root structure has developed). This stage help to explore the impact of both plant and WAP on the bacterial community before application of drought stress. Following the collection of stage 2 samples, the drought stress was imposed by stopping irrigation and the plant was allowed to wilt. In stage 3, the soil sample was collected at the end of plant wilting. This stage helps to assess the combined influence of plant, WAP and drought stress on soil bacterial community. The details of the collected soil samples are summarized in **Table 6.1.** All collected samples were stored in refrigerator at -80 °C to preserve the DNA of bacterial community in the soil. The DNA extraction was done and the sample was sent for sequencing. A detailed explanation of DNA analysis is given below.

Table 6.1: Sample codes for soil sampled at different stages of this study

Sample collection	Serial No.	Treatments	Symbols
Stage 1 (Initial condition)	1	Control soil	CS
	2	Commercial WAP +soil	CW
	3	Fly ash WAP +soil	FW
Stage 2 (Vegetative stage)	4	Control soil + plant	CS-P
	5	Commercial WAP + plant+soil	CW-P
	6	Fly ash WAP + Plant+soil	FW-P
Stage 3 (Final drought stage)	7	Soil + plant + drought stress	CS-P-D
	8	Commercial WAP + plant +drought stress	CW-P-D
	9	Fly ash WAP + plant + drought stress	FW-P-D

6.2.3) Energy Dispersive X-ray (EDX)

The Energy Dispersive X-ray (EDX) analysis was used for the elemental analysis based on the generation of X-rays that exposes the elements present in the soil matrix. The element analysis of soil were obtained using a field emission scanning electron microscope (FESEM) (Zeiss Gemini 300, Oberkochen, Germany). The samples were mounted on aluminum stubs coated with double-sided carbon tape for EDX analysis. Soil samples were kept in an oven for 24 hours at 110 degrees Celsius, to avoid the sample becoming charged during analysis.

6.2.4) DNA extraction, sequencing, and sequence data analysis

Soil and rhizosphere DNA extraction was performed using the HiPurA Soil DNA Purification Kit (Cat. No. MB542, HIMEDIA) according to the manufacturer's protocol. It is worth noting that humic substances present in the extracted DNA can potentially interfere with downstream experiments. To mitigate this issue, the extracted total soil DNA was further purified using the phenol-chloroform method. The integrity and quality of the purified total DNA were assessed using both nanodrop-based spectrophotometric analysis and gel electrophoresis. Nanodrop spectrophotometry was used to measure the DNA concentration and evaluate its purity based on the absorbance ratios at different wavelengths. Gel electrophoresis was performed to visualize the DNA fragments and assess their size distribution. For the amplification of the V3-V4 region of the 16S ribosomal gene, fusion primer was used on 12.5 ng of extracted DNA. Using Nextera XT index kit (Illumina), sequencing libraries were prepared from amplified V3-V4 regions of 16s rRNA whereby high sensitivity D1000 screen tape in 2200 TapeStation (Agilent) was used to ascertain the quality of the generated library. Sequencing of these libraries were performed in Illumina Novaseq 6000 after final library quantification was performed in Qubit Fluorometer. Sequencing data were analyzed using QIIME 2 software which was developed by the Caporaso Lab at Northern Arizona University. It is a powerful and decentralized microbiome analysis in various aspects including improved taxonomic classification accuracy.

6.3) Results and discussion

6.3.1) Microbial diversity analysis

Microbes are organized in a hierarchical taxonomic structure based on their genetic make-up, evolutionary relationships, and subsequently their functional similarities and dissimilarities (Hugenholtz et al., 2021). Members are broadly co-related in higher taxonomic levels with the degree of similarity increasing amongst members with lowering of the taxonomic levels (Philippot et al., 2010). The typical taxonomic levels are organised in the following ranking order: domain (Level 1), Phylum (Level 2), class (level 3), order (level 4), family (level 5), genus (level 6), and species (level 7).

Figure 6.1 depicts the microbial diversity for all the treatments at taxonomic level 2. The bacteria members that accounted for 90% of the total abundance at this taxonomic level were thoroughly investigated. The remainder have been grouped together as "others." The following bacteria members are listed in decreasing order of abundance: Proteobacteria

> Acidobacteria > Actinobacteria > Chloroflexi > Planctomycetes > Bacteroidetes > Gemmntinonadetes > Verrucomicrobia. Rokubacteria, Firmicutes, Nitrospirae, and other phyla which were less than 2% in abundance individually were grouped together as “others”. The “others” contributed to 10% of the relative abundance. These bacteria members are most commonly found in agricultural soil with higher abundance (Burns et al., 2015). It was observed that the distribution of the bacterial community affected by different amendments. Consistently, the most dominant bacteria was proteobacteria in all the treatments. With the addition of WAP, the abundance of Proteobacteria, Chloroflexi, Planctomycetes, and Bacteroidetes increased in the soil, whereas Acidobacteria and Gemmntinonadetes dropped. Similar trend is reported that Proteobacteria, Chloroflexi, Planctomycetes, and Bacteroidetes increased with the WAP (Cretoiu et al., 2014; Tian et al., 2020) whereas Acidobacteria and Gemmntinonadetes reduced (Boukhatem and Tsaki, 2022). It was noted that WAP amendment has no impact on the abundance of Actinobacteria and Verrucomicrobia whereas Actinobacteria increased and Verrucomicro-

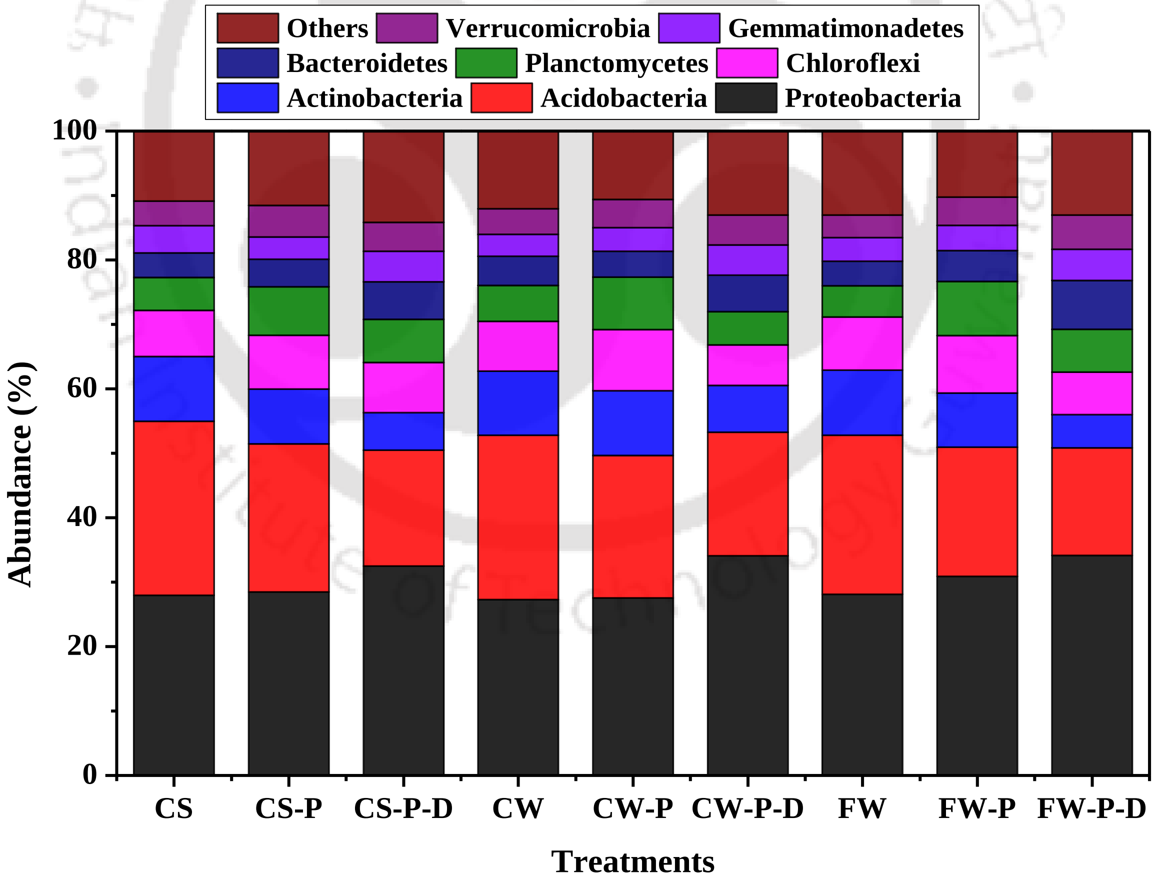


Figure 6.1: Microbial diversity analysis (taxonomic level 2) of different amended soil samples.

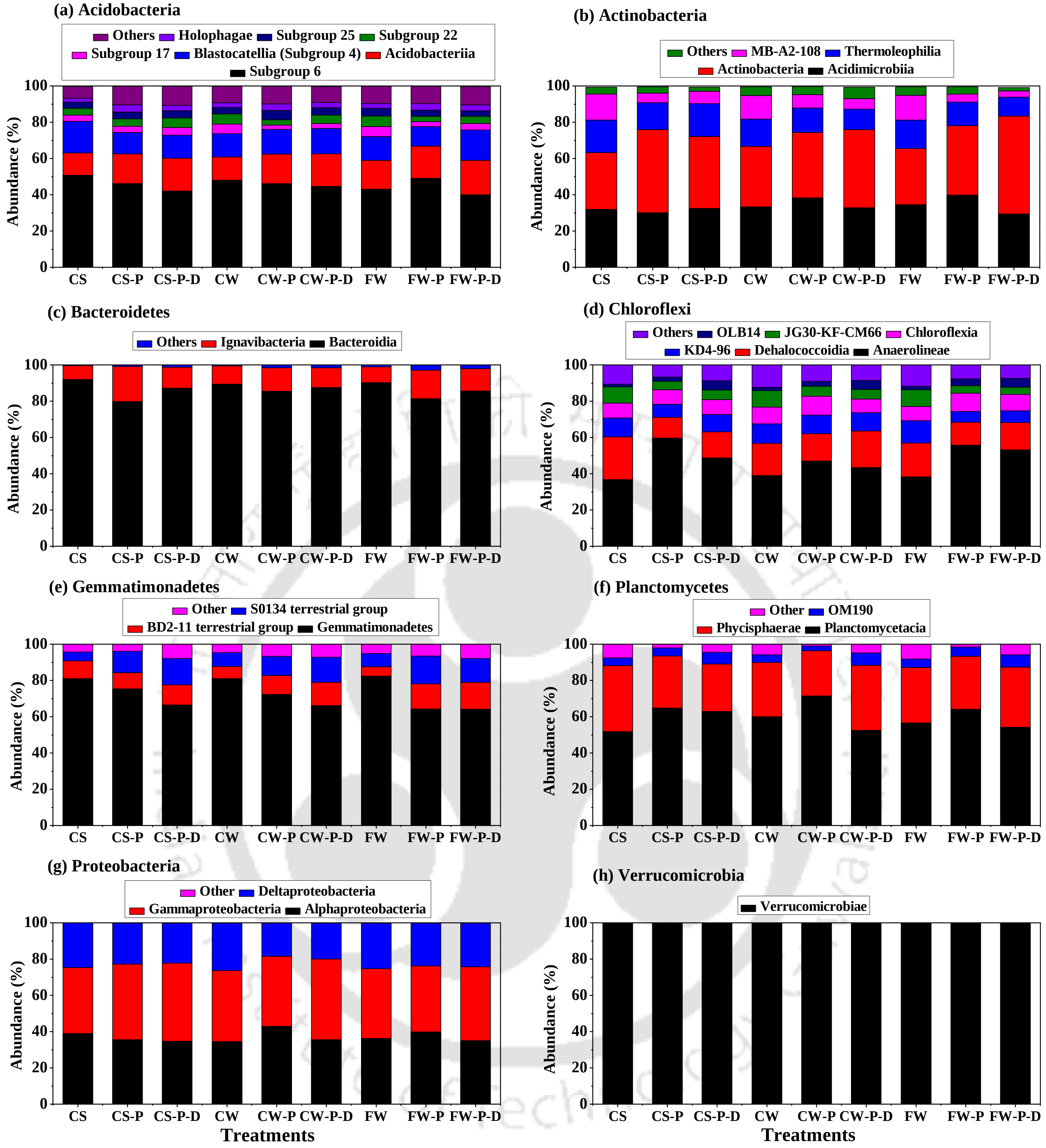


Figure 6.2: Analysis of microbial diversity at taxonomic level 3 with different amendments

-bia decreased with the presence of plant. The combined effects of WAP, plant, and drought stress have shifted the trend of bacterial abundance. With combined effect, Proteobacteria, Gemmntinonadetes, Verrucomicrobia, and Bacteroidetes were increased. However, Acidobacteria, Acitionbacteria, Chloroflexi, and Planctomycetes were reduced. **Figure 6.2** shows the important bacteria with the higher abundant occurrence, which was studied in detail at the taxonomic level 3. The findings are discussed as follows.

Acidobacteria

Subgroup 6, acidobacteriia, blastocatellia, subgroup 17, subgroup 22, subgroup 25, Holophagae and others were observed in all the treatments as shown in **Figure 6.2 (a)**. The acidobacteria phyla is the most prominent population in subgroup 6. The abundance of acidobacteriia and subgroup 17 were increased with WAP-treated soil, while Blastocatellia and subgroup 6 decreased. A similar trend was reported that acidobacteriia and subgroup 17 decreased with the amendment of WAP (Santos et al., 2017) and Blastocatellia and subgroup 6 decreases (Huber e al., 2022). Bastocatellia was increased with combined effects of WAP, plant, and drought, while acidobacteriia and subgroup 6 followed the same trend as the WAP amendment.

Actinobacteria

Acidimicrobiia, actinobacteria, thermoleophilla, and MB-A2-108 were found in all the treatments. Actinobacteria showed more variance amongst all treated samples, ranging from 1 to 1.75 times. The Acidimicrobiia, and actinobacteria was increased with WAP-treated soil, while actinobacteria decreased with the presence of plant and combined impact of WAP, plant, and drought. A similar tendency of Acidimicrobiia, and actinobacteria were identified in the literature that was associated with the WAP amendment (Boukhatem and Tsaki, 2022; Narsing et al., 2022).

Bacteroidetes

Bacteroidia had the highest population density in this cluster, followed by ignavibacteria. Bacteroidia populations declined with the WAP amendment (Oliveira et al., 2022) and grew with the combined impact of WAP, plant, and drought (Santos et al, 2017). Furthermore, it was observed that Chintophagales and Cytophagales have higher abundance at taxonomic level 4 of bacteroidia. (refer **Figure 6.3**). The relative abundance varies from 9 to 14% in all treatments at taxonomic level 4. Chintophagales abundance increased with plant presence while decreased with the effect of WAP and drought. The cytophagales abundance increased in the presence of plants and drought while decreased in the presence of WAP.

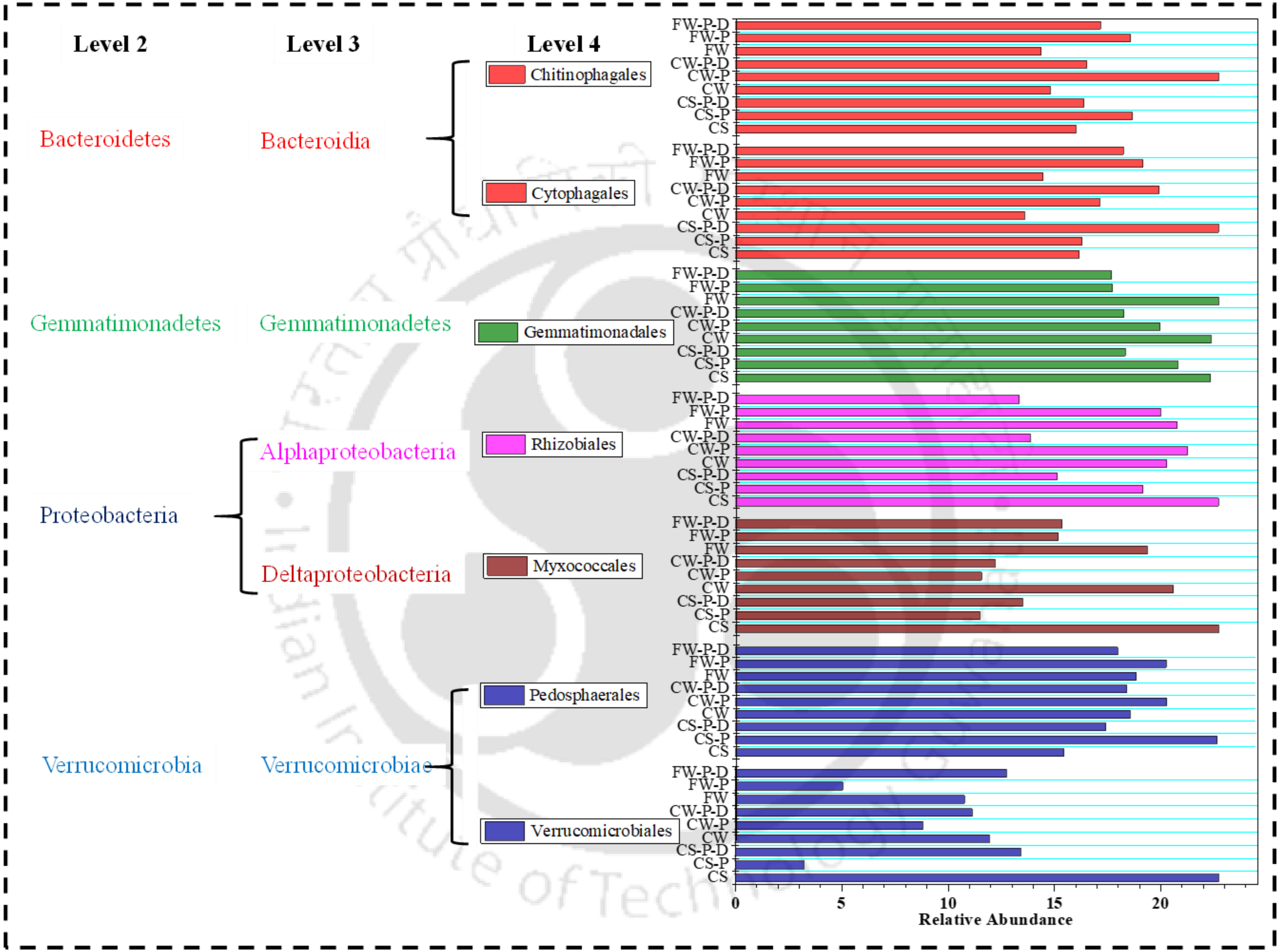


Figure 6.3: The change in relative abundance of bacterial community at the taxonomic level 4 for all the amended samples.

Chloroflexi

Anaerolineae, dehalococcoidia, KD4-96, chloroflexia, JG30-KF-CM66, OLB14, and other members were present in the chloroflexi family. The highest abundance of Anerolineae were found among the chloroflexi phylum. The variance in Anerolineae across treatments ranged from 35-60% (of the total chloroflexi population). It is observed that Anerolineae enhanced with the amendment of WAP whereas Dehalococcoidia decreased. Similarly, previous studies reported that Anerolineae increases with WAP (Zhang and Guan, 2022) and Dehalococcoidia reduced (Yang et al., 2023). With the combined effect of WAP, plant, and drought, the trend of Anerolineae and Dehalococcoidia were reversed.

Gemmatimonadetes

Gemmatimonadetes bacteria include the Gemmatimonadetes, BD2-11 terrestrial group, S0134 terrestrial group, and others. The Gemmatimonadetes bacteria were found dominant at taxonomic level 3. Furthermore, at taxonomic level 4, Gemmatimondales was discovered with a dominant population (refer **Figure 6.3**). Gemmatimondales account for more than 70% of the Gemmatimonadetes population at taxonomic level 2. Gemmatimondales and Gemmatimonadetes were increased with the amendment of WAP while diminished with the presence of plants during drought condition. It was reported that Gemmatimondales and Gemmatimonadetes increased with organic amendment (Basrida et al., 2017) and it decreased during drought stress (Monohon et al., 2021). Gemmatimondales and Gemmatimonadetes bacterias were decreased with the combined effect of WAP, plant and drought.

Planctomycetes

Planctomycetes phylum includes the planctomycetacia, phycisphaerae, OM190, and others. Planctomycetacia was found highest abundance (more than 50% of total Planctomycetes bacteria), followed by the phycisphaerae and OM190. The population of planctomycetacia increased in the presence of WAP and plants, but declined during drought stress condition. It was noted that planctomycetacia reduced with drought stress in the previous literature (Naylor and Coleman-Derr, 2018; Janssen, 2006)

Proteobacteria

Alphaproteobacteria, gammaproteobacteria, deltaproteobacteria, and others were found in the proteobacteria member. The WAP amendment boosted the abundance of gammaproteobacterial and deltaproteobacterial bacteria while alphaproteobacterial bacteria decreased. A similar trend was observed with the combined effect of WAP, plant, and drought. The results of the individual effect of WAP (Liu et al., 2021) and drought (Jang et al., 2020)were found similar to the previous literature. In addition, rhizobiales bacteria was found in higher abundance in the alphaproteobacterial at taxonomic level 4 while myxococcales were identified in deltaproteobacteria (refer **Figure 6.3**). With the amendment of WAP, abundance of rhizobiales and myxococcales were reduced according to Tian et al., (2020). Myxococcales abundance were enhanced with the combined influence of WAP, plant, and drought.

Verrucomicrobia

At taxonomic level 3, the dominant population was found to be nearly 100% of verrucomicrobiae. Verrucomicrobiae population increased with WAP and plant amendment (Dai et al., 2019) whereas it was reduced during drought condition. Bogati and Walczak, 2022 reported the drought had a negative impact on the population of Verrucomicrobiae. The population of Verrucomicrobiae bacteria was increased with the combined effect of WAP, plant, and drought. The Verrucomicrobiae was studied further at the taxonomic level 4, revealing pedosphaerales and verrucomicrobiales (refer **Figure 6.3**). Pedosphaerales abundance was higher, followed by the verrucomicrobiales. The population of pedosphaerales increased with WAP and plant amendment, while it declined with the combined influence of WAP, plant, and drought. Yurgel et al., (2018) reported that the pedosphaerales abundance was increased with the presence of plants.

6.3.2) EDX analysis

The EDX was used to analyze 11 elements, including O, Si, Al, Fe, K, Mg, Ca, Na, P, Ti, and N. The detailed elemental composition for different treatments are shown in **Table 6.2.** For all treatments, the elements of oxygen (40-57%), silicon (22-26%), and aluminium (2.5-11%) have more percentages in the soil. Mukhopadhya et al., (2019) reported that a similar trend was observed of the element content present in the soil matrix. EDX is primarily utilized in this study to detect and quantify the micronutrients and macronutrients that are helpful for plant growth, such as N, P, K, Mg, Ca, Fe, and others. According to the table, the Fe, K, Mg, Ca, P, Ti, and N increased with WAP and plant amendment while it decreased during drought conditions. The variation of nitrogen, potassium, and phosphorus content from 0 to 5.8%, 2.3 to 9.2%, and 0.2 to 2.9% respectively with different treatments.

Minimal nitrogen and potassium level was recorded in the control soil (without amendment) under drought stress, whereas phosphorous content was found. The maximum concentration of nitrogen, potassium, and phosphorus were obtained in WAP treated soil with the presence of plants. The Al was reduced in the presence of WAP and plant while it increased during drought conditions, which has detrimental effect on plant growth and development. The results clearly show that the WAP amendment had positive influence on nutrients in the soil, which may aid to keep the plant healthier and increase crop output.

6.3.3) Microbial diversity influencing soil health

Soil health is dependent on various constraints including nutrients, water status, and aeration/oxygen circulation. These constraints are influenced by the change in microbial community population and elements (macro and micro-nutrients) in the soil matrix. Therefore, this study attempts to develop an understanding of change in microbial community population and elemental composition that have influenced the important cycling processes of soil, such as nitrogen, carbon, and phosphorous cycling, organic matter, toxic element degradation, fertility, plant development, etc. In this section, the following factors influencing soil health have been discussed.

Table 6.2: Details of elemental composition of soil for all the treated samples.

Elements	CS	CS-P	CS-P-D	CW	CW-P	CW-P-D	FW	FW-P	FW-P-D
O	55.9	53.2	57.2	54	46.8	52	52.6	40.2	53.6
Si	21.9	22.9	22.8	22.3	23.9	25.7	23.6	24.9	24.9
Al	10.8	6.9	10.3	8.8	3.9	8.8	7.8	2.7	7.4
Fe	4.4	5.2	3.6	5.1	7.1	4.4	5.1	9.2	4.4
K	3.8	4.7	2.3	4.1	6.1	3.8	4.1	7.3	4.1
Mg	1.4	1.6	1.5	1.6	3.1	2.3	1.6	4.7	1.8
Ca	0.3	0.5	0.7	0.6	1.5	0.7	0.5	1.7	0.5
Na	0.2	1.4	0.9	1	0	0.3	1	0	0
P	0.2	1.3	0.4	0.6	1.7	0.5	0.6	1.9	0.5
Ti	1.1	1.1	0.3	1.2	1.4	0.4	1.2	1.6	0.6
N	0	1.2	0	0.7	4.5	1.1	1.9	5.8	2.2

Carbon content

The carbon cycle regulates carbon availability and microbial metabolism, which allows to maintain soil health. The proportion and efficiency of carbon availability are influenced by the microbial community and diversity of the soil (Lian et al., 2019). It is well known that Acidobacteriia, Anaerolineae, Acidimicrobiae, and Verrucomicrobiae have shown a positive effect on the carbon cycle and carbon availability (Ren et al., 2022). Acidobacteriia, Acidimicrobiia, and Anaerolineae abundance increased with the amendment of WAP whereas Verrucomicrobiae abundance decreased. On the other hand, Acidimicrobiia and Anaerolineae were reduced with the combined effect of WAP, plant, and drought, while Acidimicrobiia and verrucomicrobiae increased. The data clearly show that the WAP amendment improved the carbon cycle with the increment of bacterias abundance whereas drought had a detrimental influence on the bacteria. A similar trend was reported in the previous literature for the carbon cycle and availability except anaerolineae which increased under drought condition (Altshule et al., 2019; Bonetti at el., 2021).

Nitrogen content

In the soil ecosystem, nitrogen is a crucial nutrient for plant growth. Nitrogen fixation is the process of converting atmospheric nitrogen into a form that plants can use (such as ammonia). This process was aided by microorganisms in the soil matrix such as bacteria, fungi, and others. Acidobacteriia, Alphaproteobacteria, Gammaproteobacteria, Deltaproteobacteria, Anaerolineae, Gemmatimonadetes, Acidimicrobiia, Actinobacteria, Bacteroidia, and Verrucomicrobiae are well-known bacteria that have positive effect on nitrogen fixation and cycling in the soil matrix (Tuesta-Popolizio et al., 2021; Antunes et al., 2021). The abundance of Acidobacteriia, Actinobacteria, Acidimicrobiae, Anaerolineae, Gemmatimonadetes, Gammaproteobacteria, and Deltaproteobacteria bacteria increased with WAP amendment, whereas Alphaproteobacteria, Bacteroidia, and Verrucomicrobiae dropped. However, the combined effect of WAP, plant, and drought, Acidobacteriia, Actinobacteria, Bacteroidia, Gammaproteobacteria, Deltaproteobacteria, and Verrucomicrobiae were increased while Acidimicrobiia, Anaerolineae, Gemmatimonadetes, and Alphaproteobacteria decreased. Previous literature reported that acidobacteriia, acidimicrobiia, anaerolineae, and gammaproteobacterial increased with the amendment of WAP (Pongsilp and Nimnoi, 2020; Yang et al., 2023). Elemental analysis revealed that the nitrogen percentage increased in the presence of WAP and plants while decreased during drought condition (refer to table 6.2). The maximum percentage of nitrogen was observed to be 5.8% with WAP and plants. It is obvious that the WAP has improved nitrogen cycling and fixation, which aids in plant development and soil fertility.

Phosphorous content

Phosphorus is a vital mineral for plant growth and root development that is found in the soil matrix as phosphate ions. It mostly affects root development during the early stage of plant growth, such as germination, seedling, and flowering (Jin et al., 2005). Phosphorus cycling is influenced by the Subgroup 6, Gemmatimonadetes, Planctomycetes, Gammaproteobacteria, which affects the plant respiration system, energy transmission, and metabolism of plant (Huang et al., 2019; Silveria et al., 2021). With the application of WAP, abundance of Gemmatimonadetes, Planctomycetes, and Gammaproteobacteria increased, but subgroup 6 dropped. However, abundance of Subgroup 6, Gemmatimonadetes, Planctomycetes was decreased under drought stress. Similarly, Zhang and Guan, (2022) reported that Gemmatimonadetes, Planctomycetes, and Gammaproteobacteria increased with the WAP amendment. And Monohon et al., (2021) reported Gemmatimonadetes, Planctomycetes decreased under drying condition. Gammaproteobacteria was increased with the combined effect of WAP, plant, and drought. On the other hand, phosphorus element percentage increased with WAP amendment and declined under drought stress. The percentage of phosphorus element increased from 0.2 to 1.9 in the presence of WAP and plant. It clearly indicate that the WAP can boost phosphorus availability and uptake in the soil matrix, as well as the activity of the microbial community. This would aid in plant development and agricultural productivity, preserving soil fertility and aiding sustainable agriculture.

Organic matter content

In general, organic matter is composed of plant and animal residue, such as plant roots, leaves, and animal remnants. Organic matter decomposition plays an important role in the soil for maintaining soil fertility and productivity (Biswas and Kole, 2017). During decomposition, it releases important nutrients and minerals, which are mostly carried out by soil microorganisms like bacteria and fungi (Geisseler et al., 2010). Abundance of Acidobacteriia, Gemmatimonadetes, and Planctomycetacia bacterias are influenced by the decomposition of organic waste (Pide et al., 2022; Ren et al., 2022). Acidobacteriia, Gemmatimonadetes, and Planctomycetacia increased with the application of WAP in the current study. Barnard et al., (2013) reported that the Acidobacteria enriched with the WAP amended soil. Acidobacteriia increased with the addition of WAP, plant, and drought, while Gemmatimonadetes and Planctomycetacia declined. The soil moisture is critical in the organic matter decomposition process. WAP can retain moisture, which helps speed up the decomposition process and promote nutrient cycling (Wu et al., 2021). It can be concluded that the WAP has aided in the decomposition of organic materials.

Miscellaneous

Chloroflexi bacteria indirectly influenced photosynthesis, which is essential for nutrients and plant growth. Some chloroflexi member, such as green non-sulfur bacteria resemble chlorophyll pigment and aid in photosynthesis (Bryant and Frigaard, 2006). The chloroflexi bacteria grew in response to WAP amendment. However, it is found to reduce under drought stress. Similarly, Ullah et al., (2019) was noticed that chloroflexi dropped under drying condition. In addition, soil structure and fertility, are significant characteristics of soil health that have a direct impact on plant development and production. It is well known that the abundance of Acidobacteriia, Anaerolineae, and Planctomycetacia (at taxonomic level 3) has direct impact on soil fertility and structure. According to this study, Acidobacteriia, Anaerolineae, and Planctomycetacia were increased with the amendment of WAP. Similarly, Zhang et al., (2023) reported Acidobacteriia and Anaerolineae bacteria abundance increased with the amendment of WAP. Under drought stress, Anaerolineae and Planctomycetacia were reduced. It has been noticed that the WAP has aided in the preservation of soil fertility and structure.

Sulphur is an essential ingredient for the production of numerous amino acids, proteins, and enzymes that influence plant growth and development. Microorganisms influence the sulphur cycle by metabolizing sulfur-containing substances (Chaudhary et al., 2023). It is reported in the literature that Gammaproteobacteria and Deltaproteobacteria were found to influence the sulphur cycle (Wasmund et al., 2017). In the present study, Gammaproteobacteria and Deltaproteobacteria increased with WAP and combined effect of WAP, plant, and drought. Bechtold et al., (2021) reported that the Gammaproteobacteria positively correlate with WAP and drought condition. Gammaproteobacteria help to promote soil health by decomposing harmful substances in the soil (Vida et al., 2020). WAP contributes more to the breakdown of hazardous substances by boosting the Gammaproteobacteria population. Furthermore, lignin degradation is an essential step for nutrient cycling that is often difficult to degrade (Chomel et al., 2016). The bacterial

Table 6.3: Summery of changes in population of functionally significant bacterial members with the treatments and compared to the previous literature with their significance

Level	Bacteria list	Significance	W		P		W + P		P + DS		W + P + DS		Literature
			C	L	C	L	C	L	C	L	C	L	
Level 2	**Acidobacteria**	Cycling of carbon and nitrogen, decomposition of organic matter,	**D**	**D**	**D**	**D**	**D**		**D**	**D**	**D**		Bogati, K., & Walczak, M. (2022); Tian etal., 2020; Barnard et al., 2013
Level 3	**Acidobacteriia**	Cycling of carbon and nitrogen, decomposition of organic matter,	**I**	**I**	**I**		**I**		**I**		**I**		Santos-Medellín et al, 2017
	Blastocatellia (Subgroup 4)	Produce extracellular enzymes	**D**		**D**		**D**		**I**	**I**	**I**	**I**	Huber e al., 2022
	Subgroup 6	Cycling of phosphorus	**D**		**D**		**I**		**D**		**D**		
Level 2	**Actinobacteria**	Soil health and nutrient cycling	**NC**	**D**	**D**	**D**	**D**		**D**	**D**	**D**		Boukhatem &Tsaki, (2022); Zhang et al., (2019); Narsing et al., (2022)
Level 3	**Acidimicrobiia**	Degradation of lignin, cycling of nitrogen and carbon	**I**	**I**	**D**		**I**		**I**	**I**	**D**		Boukhatem and Tsaki, (2022); Zhang et al., (2019); Nimaichand et al., (2016)
	Actinobacteria	Soil health and nutrient cycling	**I**		**I**		**I**		**D**		**I**		
Level 2	**Bacteroidetes**	Both nitrogen fixation and denitrification in soil ecosystems	**I**	**I**	**I**		**I**		**I**	**D**	**I**		Cretoiu et al., (2014), Tian etal., (2020)
Level 3	**Bacteroidia**	Both nitrogen fixation and denitrification in soil ecosystems	**D**	**D**	**D**		**D**		**I**	**D**	**I**		Oliveira et al., (2022); Santos et al., (2017)
Level 2	**Chloroflexi**	Ability to carry out photosynthesis , carbon and nitrogen fixation	**I**	**I**	**I**		**I**		**D**	**D**	**D**		Cretoiu et al., (2014), Tian etal., (2020)
Level 3	**Anaerolineae**	Cycling of carbon and nitrogen, enhance soil fertility	**I**	**I**	**I**		**I**		**D**	**I**	**D**		Zhang et al., (2023); Santos et al., (2017)
	Dehalococcoidia	Detoxify chlorinated compounds	**D**		**D**		**D**		**I**		**I**		
Level 2	**Gemmatimonadetes**	Cycling of carbon and nitrogen, decomposition of organic matter, availability of phosphorus	**D**		**D**	**C**	**I**	**I**	**I**		**I**	**I**	Cretoiu et al., (2014); Oliveira et al., (2022); Youssef & Elshahed, (2009)

Level 3	**Gemmatimonadetes**	Decomposition of organic matter, availability of nitrogen and phosphorus in soil	**I**		**D**		**D**		**D**		**D**		
Level 4	**Gemmatimonadales**	Cycling of carbon and nitrogen, decomposition of organic matter, availability of phosphorus	**I**		**D**		**D**		**D**	**D**	**D**		Monohon et al., (2021); Basrida et al., (2017)
Level 2	**Planctomycetes**	Availability of nitrogen and phosphorus in soil, decomposition of organic matter	**I**		**I**	**I**	**I**		**D**	**D**	**D**		Narsing et al., (2022), Jang et al., (2020); Naylor & Coleman, (2018); Zhang & Guan, (2022)
Level 3	**Planctomycetacia**	Long-term fertilized, decomposition of organic matter	**I**		**I**		**I**		**D**		**D**	**D**	Janssen, (2006)
Level 2	**Proteobacteria**	Plant-microbe interactions, degrading toxic elements, cycling of nitrogen	**I**	**I**	**I**		**I**		**I**	**D**	**I**		Amina et al., (2021); Yuste et al., (2014); Hartmann et al., (2017); Martínez et al., (2014)
Level 3	**Alphaproteobacteria**	Conversion of ammonia to nitrite, degrading toxic elements, nitrogen cycling	**D**	**D**	**D**		**I**		**D**	**I**	**D**		Santos et al., (2017); Liu et al., (2021)
	Deltaproteobacteria	Degrading toxic elements, maintain sulfur cycle, phosphate solubilization, nitrogen cycling	**I**		**D**		**D**	**D**	**D**	**D**	**I**		Bogati and Walczak, (2022)
	Gammaproteobacteria	Nitrogen retention in soil, conversion of nitrate to nitrogen gas, oxidation of sulfide to sulfate	**I**	**I**	**I**		**D**		**I**	**I**	**I**		Bechtold et al., (2021)
Level 4	**Rhizobiales**	Increase in yield, decomposition of organic matter, nitrogen fixation process	**D**	**D**	**D**		**D**		**I**	**I**	**D**		Liu et al., (2021)
	Myxococcales	Resistant to environmental stresses, decomposition of plant debris	**D**	**D**	**D**		**D**		**I**	**I**	**I**		Tao et al., (2019)
Level 2	**Rokubacteria**	Degradation of recalcitrant organic compounds	**I**	**I**	**D**		**D**		**D**	**D**	**D**		Tian et al., (2020)
	Verrucomicrobia	Nitrogen fixation process, soil carbon content	**NC**		**I**		**I**		**D**	**D**	**I**		Dai et al., (2019); Bogati and Walczak, (2022)
Level 3	**Verrucomicrobiae**	Nitrogen fixation process, soil carbon content						**D**					
Level 4	**Pedosphaerales**	Soil health and nutrient cycling, soil carbon content	**I**		**I**	**I**	**I**		**D**		**D**		Yurgel et al., (2018)

Note: W- WAP, P- Plant, DS-Drought stress, I- Increases, D- Decreases, NC- Not change, C- Current study, L- Literature

Table 6.4: Detailed analysis of increasing/ decreasing factor of bacterial community for all the treated samples corresponding to the control soil.

Level	Bacteria list	CS	CS-P	CS-D	CW	CW-P	CW-D	FW	FW-P	FW-D
Level 2	**Acidobacteria**	1.00	0.85	0.66	0.94	0.82	0.71	0.91	0.74	0.61
Level 3	**Acidobacteriia**	1.00	1.35	1.49	1.06	1.32	1.47	1.29	1.45	1.54
	Blastocatellia (Subgroup 4)	1.00	0.67	0.73	0.74	0.79	0.81	0.75	0.62	0.96
	Subgroup 6	1.00	0.91	0.83	0.94	0.91	0.88	0.85	0.97	0.79
Level 2	**Actinobacteria**	1.00	0.84	0.58	0.99	1.00	0.72	1.00	0.82	0.50
Level 3	**Acidimicrobiia**	1.00	0.94	1.02	1.04	1.19	1.03	1.08	1.24	0.92
	Actinobacteria	1.00	1.47	1.27	1.07	1.16	1.38	1.02	1.23	1.73
Level 2	**Bacteroidetes**	1.00	1.11	1.51	1.17	1.04	1.46	1.02	1.23	1.93
Level 3	**Bacteroidia**	1.00	0.87	0.95	0.97	0.93	0.95	0.98	0.89	0.93
Level 2	**Chloroflexi**	1.00	1.17	1.08	1.08	1.32	0.87	1.15	1.24	0.92
Level 3	**Anaerolineae**	1.00	1.62	1.32	1.06	1.27	1.18	1.04	1.52	1.44
	Dehalococcoidia	1.00	0.48	0.61	0.75	0.64	0.86	0.80	0.53	0.64
Level 2	**Gemmatimonadetes**	1.00	0.81	1.12	0.81	0.86	1.10	0.86	0.91	1.14
Level 3	**Gemmatimonadetes**	1.00	0.93	0.82	1.00	0.89	0.82	1.02	0.79	0.79
Level 4	**Gemmatimonadales**	1.00	0.93	0.82	1.00	0.89	0.82	1.02	0.79	0.79
Level 2	**Planctomycetes**	1.00	1.46	1.31	1.08	1.59	1.00	1.01	1.63	1.29
Level 3	**Planctomycetacia**	1.00	1.25	1.21	1.16	1.38	1.02	1.09	1.24	1.05
Level 2	**Proteobacteria**	1.00	1.01	1.16	1.07	0.98	1.21	1.03	1.09	1.21
Level 3	**Alphaproteobacteria**	1.00	0.91	0.89	0.89	1.10	0.91	0.93	1.02	0.90
	Deltaproteobacteria	1.00	0.92	0.90	1.07	0.75	0.81	1.02	0.96	0.98
	Gammaproteobacteria	1.00	1.15	1.18	1.07	1.06	1.22	1.06	1.00	1.12
Level 4	**Rhizobiales**	1.00	0.84	0.67	0.89	0.94	0.61	0.91	0.88	0.59
	Myxococcales	1.00	0.51	0.59	0.91	0.51	0.54	0.85	0.67	0.68
Level 2	**Rokubacteria**	1.00	0.81	0.64	1.10	0.66	0.64	1.35	0.54	0.40
	Verrucomicrobia	1.00	1.28	1.18	1.04	1.16	1.22	0.92	1.15	1.38
Level 3	**Verrucomicrobiae**	1.00	1.28	1.18	1.04	1.16	1.22	0.92	1.15	1.38
Level 4	**Pedosphaerales**	1.00	1.47	1.13	1.20	1.31	1.19	1.22	1.31	1.16

community is a significant component in the degradation of substances (Ramirez-Villanueva et al., 2015). It has been found that Acidimicrobiia affected lignin breakdown in soil (Liu et al., 2022). The WAP has enhanced the population of Acidimicrobiia, which stimulates lignin breakdown in the soil. **Table 6.3 and Table 6.4** summarises the population of bacteria altered by the treatments (WAP, plant, WAP+ plant, plant + drought, WAP + plant + drought) and compared to the previous literature with their significance.

Overall, it is found that WAP has boosted bacterial population in a positive manner, nutrient cycling (carbon, nitrogen, and phosphorus), organic matter decomposition, and soil fertility under drought stress. The changes in microbial profile due to different WAP (CW and FW) was very marginal. No specific or significant trend was noticed from the bacterial analysis that can be contributed to the WAP type.

6.4) Conclusions

Soil conservation and management is a challenging task under extreme climatic conditions including drought stress and heat waves. Currently, WAP is frequently used to mitigate these critical situations and improve soil health. The soil microbial community has been influenced by the amendment of WAP. Therefore, there is a need to investigate the influence of WAP on the soil microbial community under drying condition. This study contributes to this emerging field of soil microbial community investigation through 16S rRNA gene Sequencing for different soil treatments. The study shows the impact of WAP, plant, and drought stress on the composition and diversity of the soil bacterial community. Our finding shows that the Chloroflexi, Planctomycetes, and Bacteroidetes members were increased with the WAP-amended soil, while Acidobacteria and Gemmntinonadetes decreased. For the combined effect of WAP, plant, and drought, Proteobacteria, Gemmntinonadetes, Verrucomicrobia, and Bacteroidetes were increased while Acitionbacteria, Chloroflexi, and Planctomycetes decreased. The enrichment of bacteria's abundance helps to maintain/ sustain the nutrient cycles, which promotes plant growth and development. This study observed 5.8%, 9.2%, and 2.9% of nitrogen, potassium, and phosphorus, respectively in the WAP amended soil in the presence of plants. Therefore, this study undoubtedly proves that the WAP can boost the carbon cycle, nitrogen cycling and fixation, phosphorus availability and uptake in the soil matrix, as well as the activity of the microbial community in a positive manner. This would aid in plant development and agricultural productivity, preserving soil fertility and aiding sustainable agriculture. Further research aimed at understanding the causes and consequences of WAP-amended soil considering different soils and plant species on soil microbial community is needed for improving the understanding on soil-WAP-plant–bacterial interactions.

Chapter 7

Alternate drying-wetting of soil amended with WAP and its impact on WAP performance

7.1) Introduction

It is well-known that WAP is a three-dimensional network structure, which can retain and store large amount of water. Various salt ions and impurities present in the soil and water can interact with the hydrophilic groups of WAP network. This interaction weakens the bond between the polymer network, which leads to degradation of polymer chain and reduces the water absorbing capacity with time (Siriwatwechakul et al., 2012; Saha et al., 2021a). The reduction of water absorbing capacity can influence the water retention behavior of the WAP-amended soil, which in turn alters the SWCC of the amended soil with time. Therefore, it is important to quantify the change in SWCC with multiple drying-wetting cycles of WAP amended soil.

The degradation of WAP is one of the important factors to consider before its application in the field to know the frequency of amendment. Previous studies have highlighted that WAP has improved soil properties including soil density, hydraulic conductivity, and soil water retention behaviour (Gao et al., 2007; Saha et al., 2021c). The influence of WAP on plant parameters including phenotypical, stomatal conductance, photosynthetic yield, and microbial community was studied (Albalasmeh et al., 2022; Garg et al., 2022). Sharmah and Karak (2020) reported that synthesized WAPs are non-biodegradable and remain in the soil for a long time. Recent studies have highlighted that the WAPs developed from the natural materials like starch, cellulose and clay are biodegradable (Bao et al., 2011). There are no studies on the long-term effect of WAP on soil properties.

Keeping this in view, a systematic study was planned to understand the WAP degradation kinetic and subsequent reduction in the water retention capacity of the WAP amended soil. Two different WAPs (CW and FW), and two soil textured (silt loam and silt) were selected for this study. The present study proposed a simple method to evaluate the degradation of WAP indirectly by measuring the water holding capacity of WAP and soil-water characteristics curve (SWCC), subjected to multiple drying-wetting cycles. Furthermore, SWCC can be used to infer the variation in saturation water content (SWC), field capacity (FC) and permanent wilting point (PWP) subjected to multiple drying-wetting cycles that can be used to quantify plant available water content (PAWC) and permanent wilting time (PWT).

7.2) Materials and methodology

7.2.1) Soil and WAP properties

Two different types of soils were collected from the North-eastern region of India. Soil 1 [Agriculture Soil (AS)] was collected from Brahmaputra river bank near IIT Guwahati campus, Assam, India while soil 2 [Brahmaputra Silt (BS)] was collected from Kamrup district, Assam, India. The details characterization of the used soil is presented in the chapter 3. The soils were classified as silt loam (AS) and silt (BS) according to the USDA classification. Two different WAPs were used in this study, which include (i) in-house synthesized fly ash WAP (FW) and (ii) commercially available WAP (CW). The basic characterization of WAPs are discussed in Chapter 3.

7.2.2) Measurement of water absorbing capacity (multiple drying-wetting cycle)

The water absorbing capacity and re-swelling characteristics of WAP were measured in different quality of water (distilled and tap) through multiple drying-wetting cycles. The WAC of WAP was measured by the gravimetric method (Witono et al., 2014). The dry WAP particles were added to the solution (water) and allowed to swell until WAP reached their swelling equilibrium. The excess water was drained out through filter paper under gravity. After removing the excess water, the swollen weight of WAP was measured to calculate the WAC by using equation 7.1.

$$WAC\left(\frac{g}{g}\right) = \frac{W_2 - W_1}{W_1} \qquad \text{Eq. 7.1}$$

where W_1 and W_2 = weight of dry and water-swollen WAP, respectively

The swollen WAP was then kept in hot air oven at 50°C for drying until the weight of WAP remains constant. The dry WAP was again added to the water for the measurement of WAC. This process was repeated for 12 drying-wetting cycles to determine the re-swelling behaviour of the WAP. Samples of WAP were collected for the chemical characterization such as FTIR and XRD at 1st, 4th, 8th and 12th drying-wetting cycles. Re-swelling characteristic is an important parameter to understand the degradation of WAP. The reduction in WAC influence the water retention properties of WAP amended soil.

7.2.3) Measurement of SWCC

The WAP was thoroughly dry mixed with soil to prepare WAP amended soil. The WAP amendment rate of 0.2% of the dry soil mass was considered based on the previous literature (El-Asmar et al., 2017; Saha et al., 2020a). The prepared WAP amended soil samples were place in a bottom-perforated pot (for free drainage) with hand compaction (close to field conditions). The experimental set up was placed in a greenhouse under controlled environment condition (average temperature of 25 ˚C and relative humidity of 50%). The soil samples were irrigated to ensure near saturated and minimum matric suction. A filter paper was placed at the bottom of the pot to prevent the escape of soil particle during drainage of excess water. The SWCC was measured by continuously monitoring the soil suction and water content during drying condition. This process was repeated 12 times for investigating the influence of multiple drying-wetting cycles on SWCC of WAP amended soil. It takes around 18 months to complete the measurements of SWCC for 12 cycles (45 days for each cycle). To complete Different water content and matric suction sensors were used for the measurement of SWCC as stated in Chapter 4.

7.2.4) Chemical characterization

The chemical characterization of WAP amended soil was performed using FESEM, FTIR, and XRD to confirm the degradation of the polymer chain of the WAP with multiple drying-wetting cycles. The active functional groups of the WAP surface were identified using Fourier transform infrared (FTIR) spectroscopy in the 450 cm^{1}–4,000 cm^{1} range. Prior to analysis, the WAP particles were mixed with dry potassium bromide powder and pressed to form pellets for FTIR spectrum measurement. The X-ray diffraction (XRD) technique was used to characterize the mineralogical compositions. The amended soil sample's' XRD spectra were obtained using a Rigaku X-ray diffractometer (Tokyo) with a measurement range of 2θ from 5° to 80°. The surface morphology of the soil samples was obtained using field emission scanning electron microscopy (FESEM) (Gemini 300, Carl Zeiss, Germany). Prior to FESEM analysis, the soil samples were oven-dried to avoid sample charging, and soil samples mounted on aluminium stubs over double-sided carbon tape followed by double gold coating using a sputter coater (Quorum, SC7620, Quorum Technologies, Lewes, UK and Edwards, RV3, Czech Republic). FESEM images depict the microstructural changes in soil pores caused by WAP degradation in soil.

7.3) Results and discussion

7.3.1) Re-swelling characteristics and WAC of WAP

The re-swelling capacity of WAP was investigated through 12 drying-wetting cycles reported in **table 7.1**. The maximum WAC of FW in distilled and tap water was 321 g/g and 233 g/g, respectively. Similarly, 455g/g and 373 in distilled and tap water of CW. The swelling mechanism is primarily governed by the osmotic pressure difference between the WAP network and the external solution (Zhang et al., 2007, 2014). It is well known that WAP consists of various hydrophilic groups which induce electrostatic repulsion among them and causes an osmotic pressure difference (Feng et al., 2014). Tap water contains various impurities and salt ions, and the pressure difference between WAP and solvent decreases as compared to distilled water, resulting in a decrease in the WAC of both WAP.

Table 7.1: Re-swelling capacity of WAP in distilled water and tap water.

Treatments	**WAC (FW)**	**WAC (CW)**	**Treatments**	**WAC (FW)**	**WAC (CW)**
Distilled water	(g/g)	(g/g)	Tap water	(g/g)	(g/g)
DW1	321.0	455.5	TW1	233.0	373.1
DW2	315.5	450.1	TW2	217.7	342.6
DW3	311.2	447.7	TW3	202.4	307.9
DW4	306.8	442.1	TW4	187.1	277.9
DW5	301.9	438.4	TW5	171.8	238.1
DW6	297.2	432.1	TW6	156.5	193.3
DW7	292.5	428.8	TW7	141.2	171.8
DW8	287.8	423.5	TW8	125.9	132.6
DW9	283.1	417.8	TW9	110.6	115.1
DW10	278.5	412.9	TW10	95.3	100.3
DW11	274.2	408.3	TW11	80.0	83.4
DW12	269.1	402.4	TW12	64.7	65.3

Note: number in the symbol denotes drying-wetting cycle

The re-swelling capacity of the FW and CW showed a decrease by 16% and 12% respectively, in distilled water. Whereas in tap water significant decrement in FW and CW are 72% and 82% after 12 alternate wetting-drying cycles. The decrement rate of WAC was constant for each drying-wetting cycle. The swollen WAP was dried in an oven (at 50 °C temperature) for each drying cycle. The polymer chain is affected due to temperature that can lead to decrease in WAC. Zhao et al., (2005) reported that the WAC decreases with the increasing temperature in the range of 35-60 °C. The reason for WAC decrement in distilled water can be attributed to the temperature effect only. However, in tap water, the sharp decrease in WAC was attributed to the heating effect and interaction between salt impurities in water and polymer network, which can weaken the bond in the polymer network (Chen et al., 2020; Saha et al., 2022a).

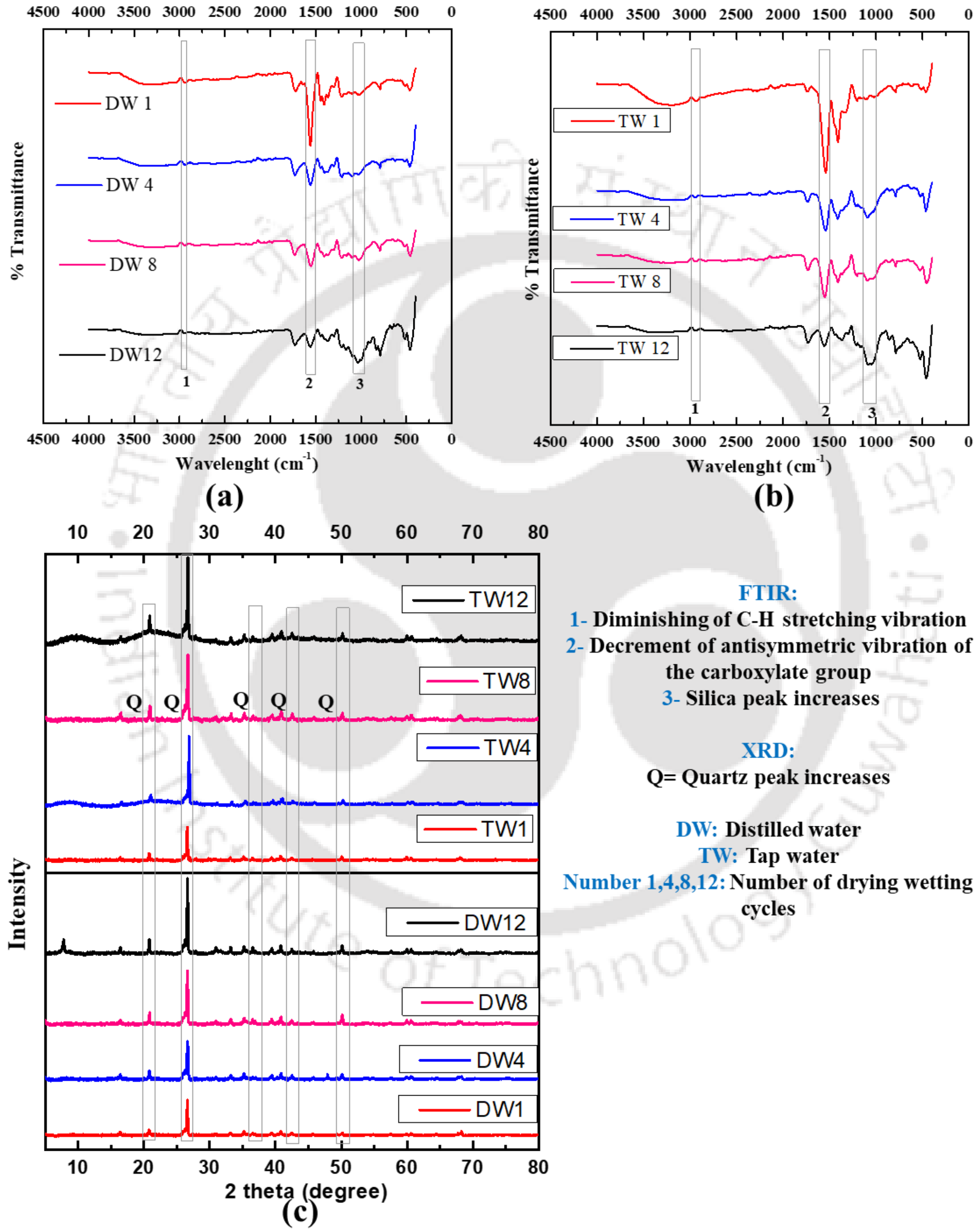


Figure 7.1: (a) FTIR in tap water, (b) FTIR in distilled water, and (c) XRD spectra (distilled and tap water) of the FW subjected to multiple drying-wetting.

For validating the above observation, the FTIR and XRD spectra of the FW after specific alternate wetting–drying cycles were carried out and presented in **Figure 7.1**. The FTIR and XRD spectra were compared for the 1st, 4th, 8th, and 12th cycle in both distilled and tap water is shown in **Figure 7.1(a), (b), and (c)** respectively. It is noticed that the intensity of characteristics peak at around 2950 cm^{-1} gradually decreased with the number of drying-wetting cycles. At mentioned peaks, the stretching vibration of C-H groups occur due to reduction of the alkane groups in the WAP network. This is mainly attributed due to the degradation of WAP and formation of single-unit acrylate ion. The vibrational frequency around 1560 cm^{-1} often corresponds to the antisymmetric vibration of the carboxylate group of the polymer. A decrease in peak intensity at this frequency could be indicative of the decrease in number of carboxylate ion in the polymer due to degradation. Furthermore, the peak at 1050 cm^{-1} confirms the presence of silicate ions. Silica peak increases with the number drying-wetting cycles. This indicates that with the degradation of WAP network, partially neutralized acrylic acid monomer get detached from the three dimensional network structure whereas fly ash particles remain in the existing

The XRD spectra shows the peak at 20.87°, 2.65°, 36.55°, 42.57°, 50.15° which confirm the quartz crystalline mineral present in the WAP structure. Quartz peaks increased with the number of drying-wetting cycles. It is well known that quartz is a hard crystalline mineral composed of silica. It gives an indication that the silica content remains constant in the WAP structure with the degradation of WAP network. Moreover, all peak intensities of FTIR and XRD spectra are higher in the tap water compared to the distilled water. These results indicate that the presence of salt ions and impurities significantly influences the water absorbency of WAP with progressive drying–wetting cycles. Therefore, the degradation of the polymer network is more in tap water as compared to the distilled water.

7.3.2) Impact of drying-wetting cycles of WAP amended soil

The measured SWCC of WAP amended soil subjected to multiple drying-wetting cycles in silt loam and silt are presented in **Figure 7.2.** The SWCCs were determined from long duration (around 45 days for each cycle) continuous measurements up to 12 drying-wetting cycles. The results of SWCC for 1st, 4th, 8th and 12th drying-wetting cycles are presented in the Figures **Figure 7.2** investigates the role of different WAPs and soil type on the SWCC of WAP amended soil subjected to multiple drying-wetting cycles. In general, silt exhibited a higher water retention than silt loam for control and WAP amended soils. This is expected due to the textural difference, wherein silt was noted to give higher water retention than silt

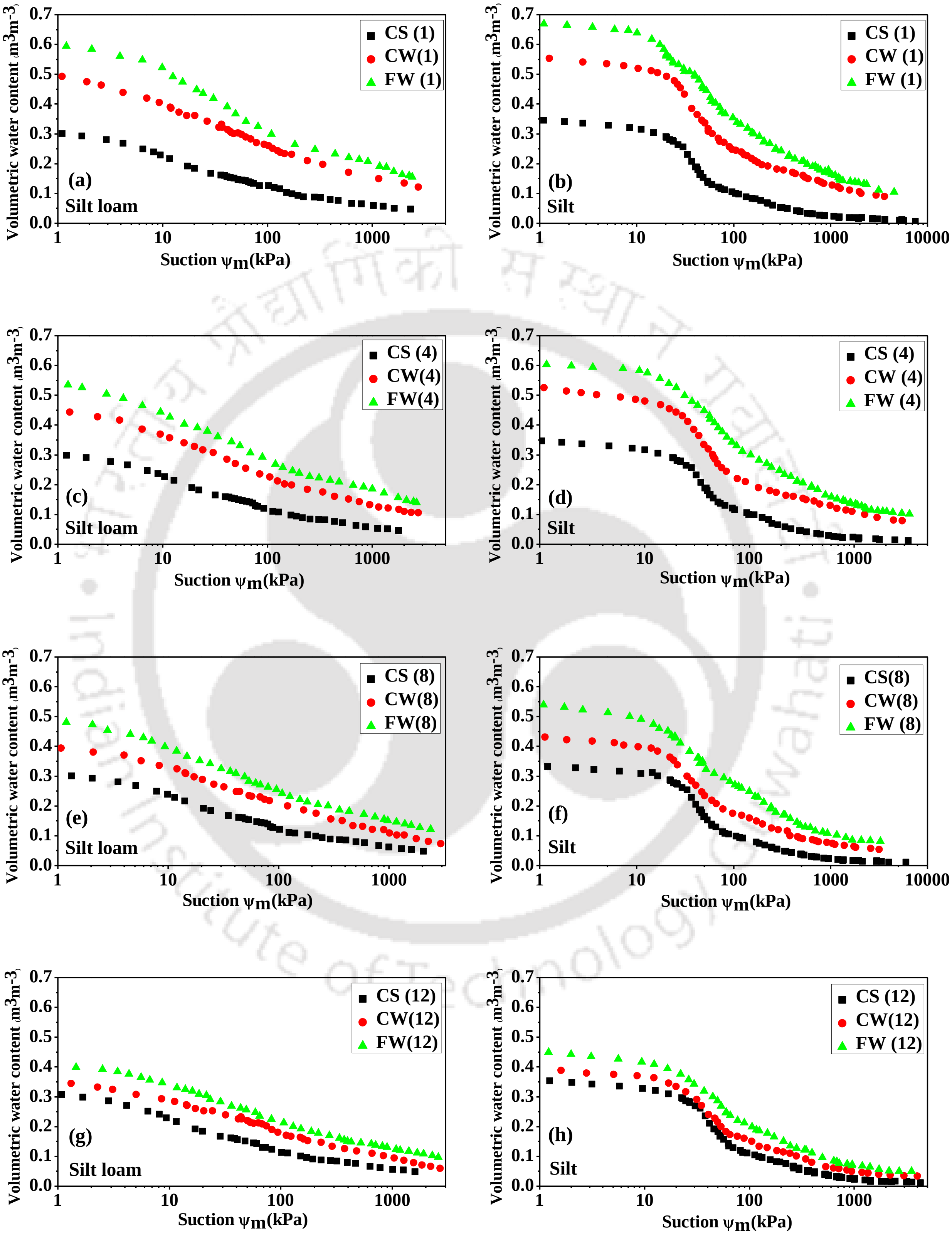


Figure 7.2: Comparison of SWCCs of different WAP (CW and FW) amended soil (a, c, e, g) silt loam and (b, d, f, h) silt subjected to wetting-drying cycles.

loam (Akhter et al., 2004). In every wetting-drying cycle, FW gave the maximum water retention followed by CW and control soil. This observation matches well with Chapter 4 (section 4.3.3) and an detailed explanation was given there. In both the soils, there is a visible difference in the SWCC of WAP amended soil showing a reduction in water retention with an increasing number of drying-wetting cycles. However, there is no change in the SWCC of both the control soils showing that the change in SWCC is entirely attributed to the degradation of WAP with increasing drying-wetting cycles.

As explained earlier, the increase in water retention capacity of WAP amended soil compared to control soil is mainly due to the swelling behaviour of WAP. The swelling is sensitive to the ionic concentration of the swelling medium. During multiple drying-wetting cycles, water retention capacity reduces due to the weakening of the chemical bond in the WAP network structure (Saha et al., 2022a). The weakening of bond when the WAP was exposed to chemicals, UV radiation, and high temperature is reported in the literature (Wang and Xing, 2007). These factors can break the polymer chain, leading to a reduction

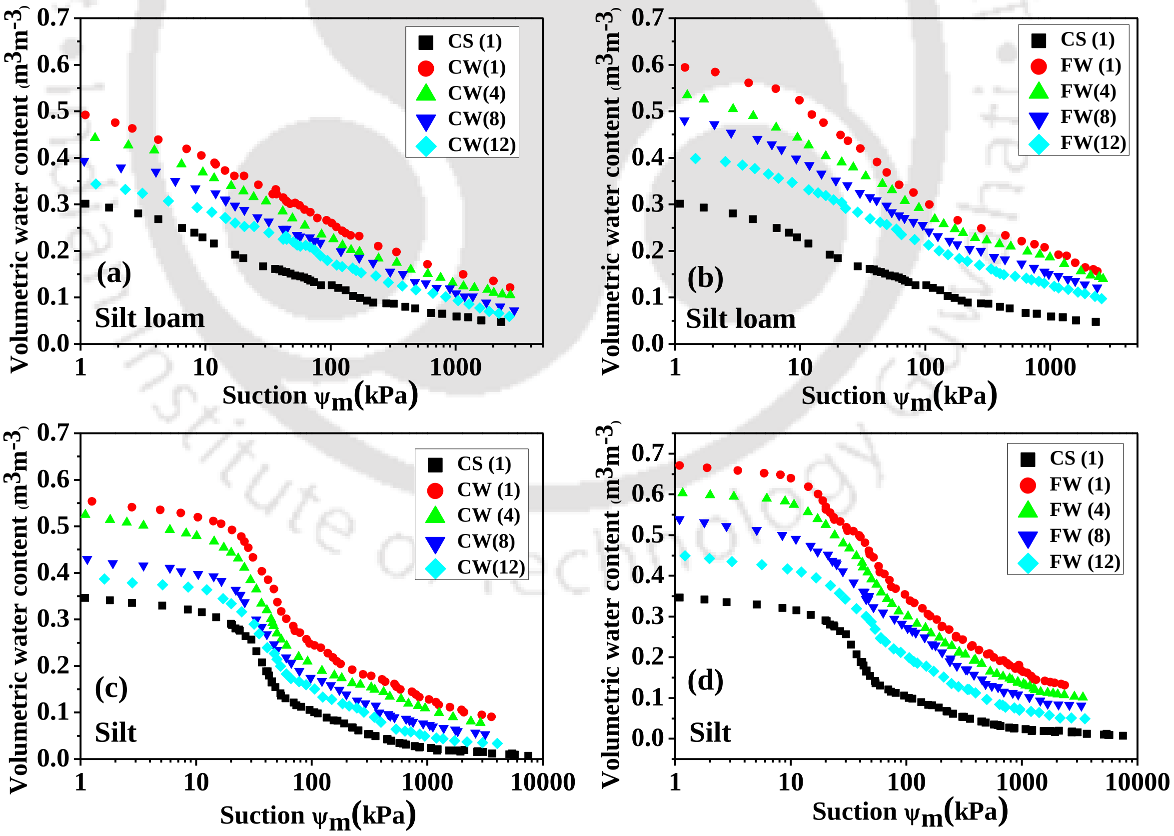
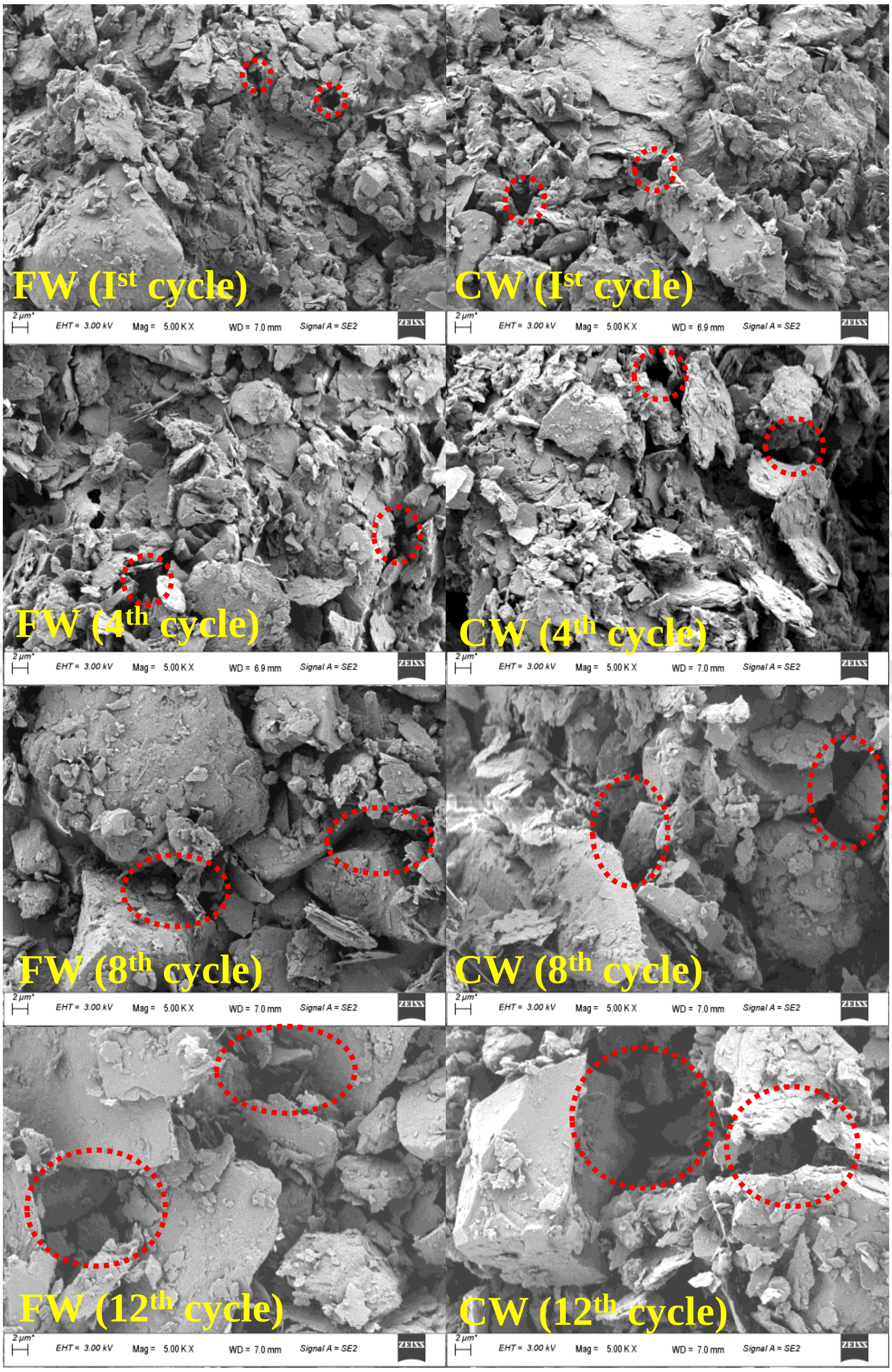
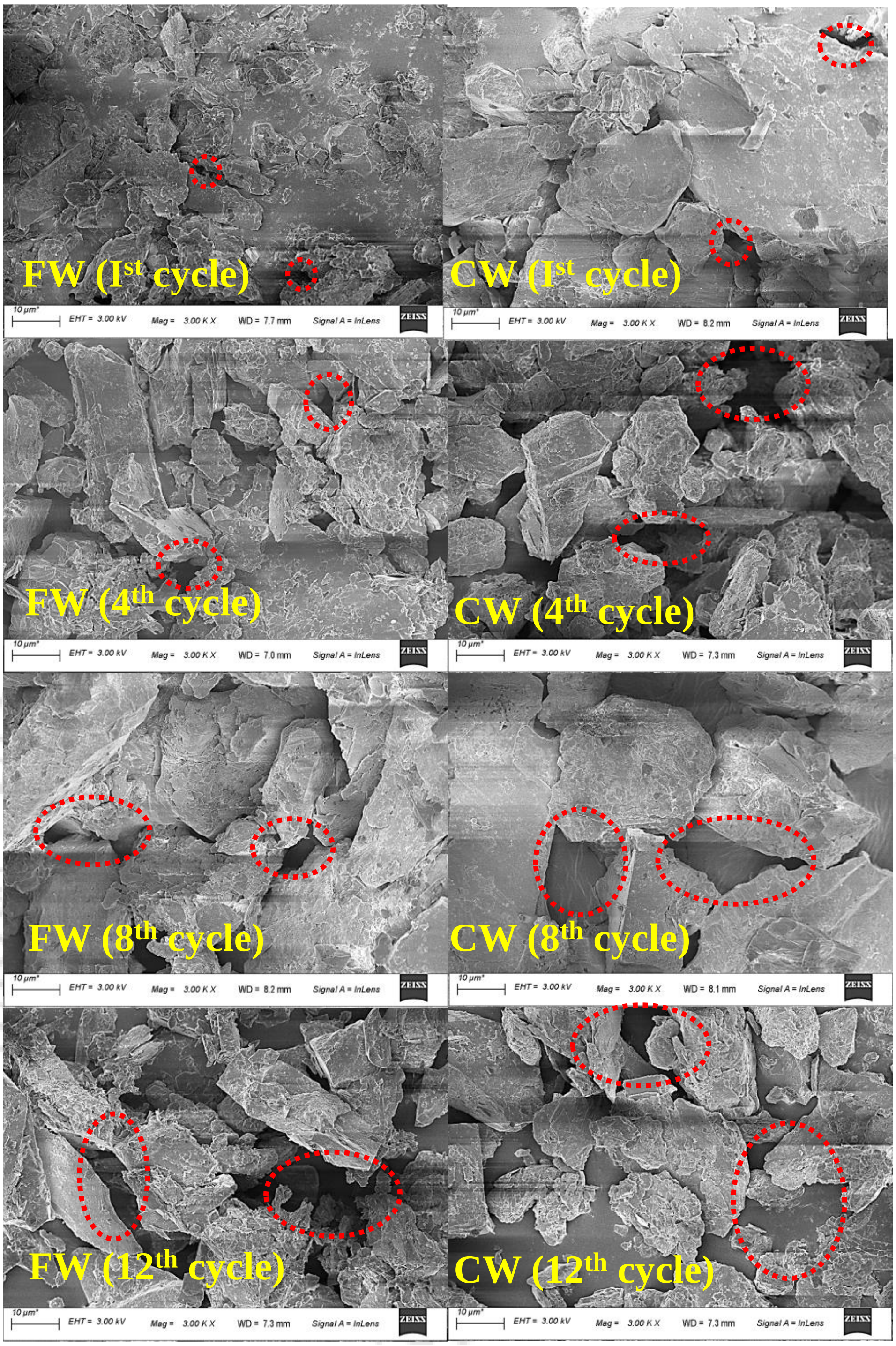


Figure 7.3: Effect of multiple drying-wetting cycles on SWCC of WAP amended soils (a, b) silt loam and (c, d) silt.

in the WAC and overall performance. The degradation of WAP influences the soil pore size, specific surface area and water bonding mechanism of soil, which subsequently alter the SWCC of WAP amended soils (Neethu et al., 2018). **Figure 7.3** shows the influence of multiple drying-wetting cycles on the SWCC of WAP amended soils. There was a broad



(a)



(b)

Figure 7.4 FESEM images of WAP-amended soils subjected to multiple drying-wetting cycles in (a) silt loam and (b) silt.

range of reduction in SWCC for FW amended soil compared to CW in both silt and silt loam. This explains the advantage of FW to withstand water retention than CW with repeated drying-wetting cycles.

To validate the reduction in water retention associated with WAP degradation, the surface morphology of the WAP amended soil was examined at the end of different drying-wetting cycles by the field emission scanning electron microscopy (FESEM) as shown in **Figure 7.4** for silt loam and silt. It can be observed from the Figure that the pore channels and voids progressively increase with increasing drying-wetting cycles for both soils. This is due to the degradation of WAP network resulting in progressive reduction in swelling during wetting. The reduction of water retention is higher in the lower suction range (ψ_m < 100 kPa) compared to the higher suction range (ψ_m > 100 kPa). It is well-known that water retention at lower suction is mainly attributed to capillary force that depends on the pore size distribution. During multiple drying-wetting cycles, the empty pores are created and increased pore size in the soil matrix due to the degradation of WAP. It is evident that the capillary force decreases due to increasing pore size in the soil matrix which may lead to reduction in the water retention capacity of soil with the progressive drying-wetting SWCC cycles. Furthermore, the WAP can increase the specific surface area (SSA) of the soil which influence the water retention capacity at higher suction range. At higher suction range, water retains on the particle surface in the form of thin film (Lu and Likos, 2004; Lu and Khorshidi, 2015). The results indicate that the water retention capacity at higher suction range decreases with the number of drying-wetting SWCC cycles. The reduction in water retention capacity is due to the decrease in specific surface area (SSA) of the soil with the degradation of WAP.

Comparing the influence of degradation on both WAPs, the FW amended soil have higher retention capacity than the CW after multiple drying-wetting cycles for both soils (silt loam and silt). CW amended soil was found to be more influenced by the multiple drying-wetting cycles, which can be caused due to its higher sensitivity to the salt ions (which are present in the soil). It is already observed that CW has more influence in tap water (without soil) compared to FW. It can be noted that the FW was developed by incorporating aluminosilicate material (fly ash) in WAP network, which leads to lower sensitivity to the salt ions presents in the soil matrix as compared to CW. It is reported in the literature that the WAP network developed with the incorporation of aluminosilicate material (e.g. bentonite, kaolin, montmorillonite) can have better mechanical properties as well as salt resistivity (Zohourian and Kabiri, 2008; Kabiri et al., 2011). Therefore, FW amended soil was less influenced during multiple drying-wetting cycles and hence can sustain higher water retention in soil for longer period.

7.3.3) Impact of multiple drying wetting cycles on the SWCC parameters

For green infrastructure/ agricultural application, various SWCC parameters are important which represent the amount of water present in the soil pores. In this study, saturated water content (SWC), field capacity (FC), permanent wilting point (PWP) and plant available water content (PAWC) were considered as the SWCC parameters for quantifying the reduction is water retention with multiple drying-wetting of WAP amended soil. The SWC defines the maximum amount of water that may be held in the soil pores at near zero suction (Lowery et al., 1997). Field capacity (FC) is the quantity of water that remains in the soil after excess water has drained out under gravity (Cassel and Nielsen, 1986). Slatyer (1967) reported the water content corresponding to a suction value of 1500 kPa as permanent wilting point. The PAWC is the arithmetic difference between the water content at FC and PWP (Vaheddoost et al., 2020).

Table 7.2 lists the details of SWCC parameters of WAP amended silt loam and silt for multiple drying-wetting cycles (1st, 4th, 8th and 12th cycles). The SWC, FC, PWP and PAWC parameters were quantified from the measured SWCC. A reduction in SWC was found with the increasing number of drying-wetting cycles in both soils and WAPs. A higher SWC was noted in WAP amended silt than WAP amended silt loam soil corresponding to a given drying-wetting SWCC cycle. This happens due to the presence of

Table 7.2: Effect of multiple drying-wetting cycles on SWCC parameters

Silt loam	CS	CW(1)	CW(4)	CW(8)	CW(12)	FW(1)	FW(4)	FW(8)	FW(12)
SWC	0.301	0.492	0.443	0.393	0.344	0.594	0.534	0.481	0.399
FC	0.163	0.326	0.292	0.261	0.234	0.411	0.361	0.321	0.278
WP	0.052	0.141	0.119	0.095	0.079	0.175	0.151	0.137	0.114
PAWC	0.111	0.185	0.173	0.166	0.155	0.236	0.21	0.184	0.164

Silt	CS	CW(1)	CW(4)	CW(8)	CW(12)	FW(1)	FW(4)	FW(8)	FW(12)
SWC	0.346	0.553	0.525	0.431	0.387	0.67	0.603	0.539	0.449
FC	0.231	0.421	0.365	0.301	0.278	0.51	0.461	0.392	0.33
WP	0.019	0.112	0.094	0.064	0.042	0.142	0.113	0.091	0.063
PAWC	0.212	0.309	0.271	0.237	0.236	0.368	0.348	0.301	0.267

higher clay content in silt loam which resists the swelling capacity of WAP (Saha et al., 2020a). The SWC reduces with the increasing number of drying-wetting cycles and follows the order of control soil < 12th cycle < 8th cycle < 4th cycle < 1st cycle. Even after 12th drying-wetting cycle, the SWC is higher in WAP amended soil than the control for both the soils. The SWC after 12th cycle is found to be 1.14 times and 1.32 times more than control soil for CW and FW, respectively in silt loam. In silt, the SWC after 12th drying-wetting cycles is found to be 1.24 times and 1.3 times for CW and FW, respectively. The SWC decreased by 30-34% from Ist to 12th alternate drying wetting cycles in both WAPs and soils. Comparing both the WAPs, the CW showed higher reduction in SWC than FW in every drying-wetting cycles. The data clearly show that WAP deterioration has a significant effect on SWC. However, WAP amended soil has stored more water in the soil pores as compare to control soil even after 12 cycles, which indicates the effectiveness of WAP under water stress conditions.

The FC, PWP and PAWC reduced with the increasing number of drying-wetting cycle and the trend followed control soil < 12th cycle < 8th cycle < 4th cycle < 1st cycle. The increasing order of PAWC in FW amended silt loam was control soil (0.111) < 12th cycle (0.164) < 8th cycle (0.184) < 4th cycle (0.21) < 1st cycle (0.236). Similarly, for FW amended silt soil, the trend follows: control soil (0.212) < 12th cycle (0.267) < 8th cycle (0.301) < 4th cycle (0.348) < 1st cycle (0.368). The results indicate that the soil texture influences the PAWC of WAP amended soil when subjected to multiple drying-wetting cycles. After 12th cycle, the PAWC was 1.47 times and 1.25 times as compared to control soil with FW amendment in silt loam and silt, respectively. On the other hand, the addition of CW has increased PAWC by 1.39 times and 1.11 times in silt loam and silt, respectively, after 12th drying-wetting cycles. The WAP was able to retain more water in silt than silt loam after repeated drying-wetting cycles for both WAPs.

7.3.4) Effect of multiple drying-wetting cycles on plant wilting time

The amount of time required to reach the permanent wilting point (i.e., plants can no longer draw water from the soil) under water stress conditions can be termed as plant survival time or plant wilting time (PWT) (Abedi-Koupai et al., 2008). The PWT (Johnson, 1984; Koupai et al., 2008) was determined from the soil suction versus time response (measured using TEROS21) during continuous drying. The time to reach the suction value of 1500 kPa was considered as the PWT. The **Figure 7.5** depicts the details of PWT of different Combinat-

-ions considered in this study. The PWT progressively decreases with the number of drying-wetting cycles in both soils (silt loam and silt). The order of PWT for FW in silt loam is 1104 hrs (1st cycle) > 1024 hrs (4th cycle) > 958 hrs (8th cycle) > 886 hrs (12th cycle) > 792 hrs (control soil). Similarly, for silt soil, the order of PWT is found to be 1080 hrs (1st cycle) > 976 hrs (4th cycle) > 856 hrs (8th cycle) > 742 hrs (12th cycle) > 608 hrs (control soil). This indicates that the PWT of WAP amended soil is influenced by both drying-wetting cycles and soil textures. The PWT in FW amended soil at 12th drying-wetting cycle is 1.12 times and 1.22 times higher than control soil for silt loam and silt, respectively. Similarly, for CW amended soil, the plant survival time is 1.07 times and 1.15 times more than control soil in silt loam and silt, respectively. The decrement in wilting time with progressive drying-wetting cycles is found to be more in CW amended in both soil due to its higher sensitivity towards the impurities and salt ions present in pore water. These results suggest that, WAP amended soil maintained more water in the soil than the

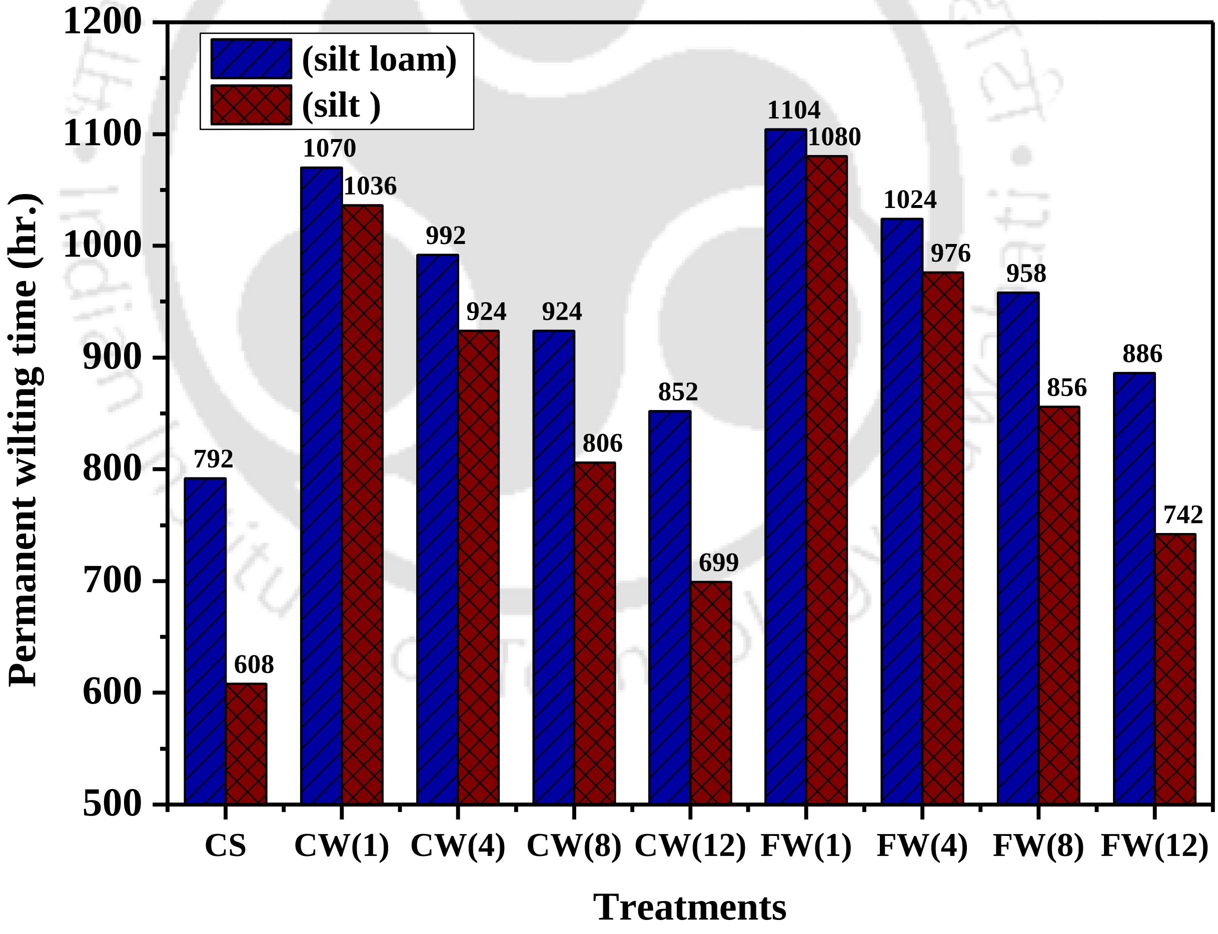


Figure 7.5: Influence of multiple drying-wetting cycles on plant wilting time

control soil even after 12 alternate drying-wetting cycles, which help to increase the survival time under water stress conditions. Therefore, application of WAP would help to reduce irrigation frequency and facilitate better plant growth. However, this study was conducted under laboratory conditions, and its application in field condition needs to be assessed.

7.4) Conclusions

This study explored the performance of WAP amended soil subjected to multiple drying-wetting cycles (12 cycles) for quantifying its impact on SWCC. The main observations of this study are listed as follows:

- The re-swelling capacity of the FW decreased by 16% and 72% in distilled water and tap water, respectively after the 12 wetting-drying cycles. A sharp decrease of WAC in tap water was attributed due to the heating effect and interaction between salt (water impurities) and polymer network.
- Analysis of FTIR spectrum of WAP showed reduction in the alkane groups in the WAP network and formation of single unit acrylate ion. In addition, the appearance of characteristics peak of acrylic monomer was found after multiple drying-wetting cycles. These peaks can be attributed to the degradation of the WAP network in the soil matix.
- A significant reduction in water retention capacity of WAP-amended soil was found with the increasing number of drying-wetting SWCC cycles in both soils. This was due to the increase in pore space associated with diminished re-swelling of WAP associated with progressive degradation.
- FW amended soil has higher water retention capacity than the CW after multiple drying-wetting cycles in soil.
- Silt has higher water retention capacity with the amendment of WAP's (for both WAP's) than silt loam.
- Due to the degradation of the WAP network, the saturated water content of WAP-amended soil decreased with alternate drying-wetting cycle.
- The increasing order of PAWC in silt loam for FW follows: control soil (0.111) < 12th cycle (0.164) < 8th cycle (0.184) < 4th cycle (0.21) < 1st cycle (0.236). Similarly, for silt soil the order of PAWC follows: control soil (0.212) < 12th cycle (0.267) < 8th cycle (0.301) < 4th cycle (0.348) < 1st cycle (0.368).

- Plant wilting time decreased with the increasing number of drying-wetting cycles in both soils. The plant survival time in FW amended soil was 1.12 times and 1.22 times higher than control soil after 12th drying-wetting cycles in silt loam and silt, respectively.

Chapter 8

Conclusions, limitations and future scope

8.1) General

This research was initiated to explore the soil-water absorbing polymer (WAP)-vegetation-atmosphere interaction for its application in bioengineered slope, green infrastructure/ urban green space and agricultural practices. The combined effects of WAP and vegetation on soil characteristics such as the water retention behaviour, soil microbial community, wilting/ plant physiology, and degradation of WAP in soil were investigated. The important conclusions are summarized below based on the systematic laboratory and field studies. The major contributions from this study are listed followed by limitations and future scope of work.

8.2) Major conclusions from this study

- The water absorbing capacity (WAC) of two WAPs (CW and FW) considered in this study decreased with an increase in fertilizer concentrations. The reduction was marginal for non-ionic urea fertilizer, whereas the ionic DAP fertilizer significantly reduced the water absorbency.
- In spite of the above conclusion, the soil-water characteristics curve (SWCC) of WAP and fertilizer amended soil showed that there is no negative influence of fertilizers on the performance of WAP in soil. The water retention was improved with the inclusion of fertilizers along with WAPs.
- The combined addition of FW and fertilizers has further increased the plant wilting time by 1.9 times and 2.3 times compared to bare soil in silt loam (AS) and silty soil (BS), respectively. This suggests a prolonged survival time for plant species under water stress conditions.
- The improvement in plant available water content (PAWC) of fertilizer and WAP amended soils indicate higher water availability to plant roots. Therefore, WAP amendment, along with fertilizers, improves the soil-water storage of soil and effectively increases the water and essential nutrients availability for plant.
- The FW was found to have higher water retention than CW due to aluminosilicate contribution.
- The plant available water content (PAWC) of FW amended soil with vegetation was higher than those of CW and control soil.

- The rate of decrease in stomatal conductance (SC) and photosynthetic yield (PY) was found to be less in WAP amended soil indicating less water stress on plants under water-deficit condition.
- It is demonstrated that SC and PY values at the beginning and end of drought are influenced by plant type, soil type, organic fertilizer, and WAP amendment under water stress condition.
- Under laboratory condition, the overall variation of soil suction at drought initiation point (SS-DIP) and (soil suction at final drought point) SS-FDP is in the range 125-229 kPa and 940-1310 kPa, respectively considering all the measurement combinations in this study.
- This study demonstrated the possibility of plant specific linear relationship between soil suction (SS), normalized stomatal conductance (NSC) and photosynthetic yield (PY) corresponding to FDP and its respective values at DIP. The SS-FDP was more specifically dependent on plant species than SS-DIP. Similarly, PY-FDP was distinctly different for plant species compared to NSC-FDP with beans showing higher values than radish.
- Yield increased more than 3 times for both plant species under water stress conditions when the soil was amended with FW in laboratory condition.
- The plant type had a pivotal role in the determination of drought related parameters than the soil type. The various soil amendments considered in this study had negligible influence on the drought related parameters
- The SS-DIP was in the range 175-250 kPa for both plant types under field condition.
- The quantification of permanent wilting point (PWP) based on SC and PY under field condition indicated wilting suction in the range of 1300 kPa - 1050 kPa for both plant types.
- The addition of FW in the soil enhanced yield more than 1.5 times under water stress for all plant types in field condition.
- The abundance of Chloroflexi, Planctomycetes, and Bacteroidetes members were increased with WAP amendment while Acidobacteria and Gemmntinonadetes decreased.
- For the combined effect of WAP, plant, and drought, Proteobacteria, Gemmntinonadetes, Verrucomicrobia, and Bacteroidetes were increased while Acitionbacteria, Chloroflexi, and Planctomycetes decreased.

- The enrichment of bacteria's abundance helps to maintain/ sustain the nutrient cycles including carbon, nitrogen, phosphorous etc, which promotes plant growth and development.
- EDX analysis observed 5.8%, 9.2%, and 2.9% of nitrogen, potassium, and phosphorus, respectively in the WAP amended soil in the presence of plants.
- The study undoubtedly proves that the WAP can boost the carbon cycle, nitrogen cycling and fixation, phosphorus availability and uptake in the soil matrix, as well as the activity of the microbial community in a positive manner.
- The re-swelling capacity of the FW decreased by 16% and 72% in distilled water and tap water, respectively after the 12 wetting-drying cycles. Similarly, for CW re-swelling capacity decreased by 12% and 82% in distilled water and tap water, respectively.
- A significant reduction in water retention capacity of WAP-amended soil was found with an increasing number of drying-wetting SWCC cycles in silt and silt loam. This was due to the increase in pore space associated with diminished re-swelling of WAP associated with progressive degradation.
- The increasing order of PAWC in silt loam for FW follows: control soil (0.111) < 12th cycle (0.164) < 8th cycle (0.184) < 4th cycle (0.21) < 1st cycle (0.236). Similarly, for silt soil the order of PAWC follows: control soil (0.212) < 12th cycle (0.267) < 8th cycle (0.301) < 4th cycle (0.348) < 1st cycle (0.368).
- The plant survival time in WAP amended soil was 1.1 times and 1.2 times higher than control soil after 12th drying-wetting cycles in silt loam and silt, respectively.
- Silt exhibited higher water retention capacity with the amendment of WAP (for both WAPs) than silt loam.

8.3) Major contributions from this study

- Explored the utility of synthesized WAP from waste material fly ash for improving water retention of soil.
- Quantified the impact of fertilizers on SWCC of WAP amended soil.
- Quantified the difference in SWCC under the combined influence of vegetation and WAP.
- Explored the influence of WAP on the water retention behavior of vegetated soil in both laboratory as well as field condition.
- Explored wilting characteristics (from saturated to dry stage) of different soils with different vegetation and WAP amendment.

- Wilting characteristics (such as drought initiation point and final drought point) were demonstrated with the help of plant physiological parameters of plant, visual interpenetration of leaves status and soil suction.
- Studied the influence of WAP and vegetation on the microbial community of unsaturated soil under water stress condition.
- Quantified the degradation of WAP in soil under multiple alternate drying-wetting cycles (12 cycles).

8.4) Limitations and future scope

- Need to explore the predictive model to estimate the SWCC under the combined influence of WAP, vegetation, and fertilizer.
- Hysteresis model that can predict the wetting SWCC of WAP and vegetation-amended soils from the measured drying curve needs to be investigated.
- Need to explore root water uptake modeling in the unsaturated soil with the combined amendment of WAP, fertilizers and vegetation.
- Need to explore the evaporation pattern in the soil with WAP-amended soil.
- Need to investigate the drought progression for different soil type, plant species with amendments (Such as WAP, fertilizers) for better understanding of their interdependency.
- Understanding the causes and consequences of WAP-amended soil considering different soils and plant species on soil microbial community is needed for improving the understanding on soil-WAP-plant–bacterial interactions
- Further studies need to be conducted to analyze the influence of WAP on plant-available nitrogen and immobility of pesticides/ insecticides

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- Rattan, B., Banerjee, A., Dhobale, K.V., Garg, A., Sreedeep, S., & Sahoo, L. (2024). Examining the soil bacterial community under the combined influence of water-absorbing polymer and plant subjected to drought stress. *Plant and soil (accepted).*
- Rattan, B., Dwivedi, M., Garg, A., Sekharan, S., & Sahoo, L. (2024). Combined influence of water-absorbing polymer and vegetation on soil water characteristic curve under field condition. *Plant and Soil*, 1-12. https://doi.org/10.1007/s11104-023-06474-w
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- Rattan, B., Ingole R., Garg, A., Wang Y., Sekharran, S., & Sahoo, L. (2023). Efficacy of water absorbing polymer manufactured from fly ash in influencing unsaturated soil properties and vegetation growth under drying Condition. Proceedings of 5th International Symposium on Unsaturated Soil Mechanics and Waste Disposal conference 2023, Tongji University, China

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- Rattan, B., Shankar, M., A., Garg, A., Sahoo, L., Pekkat, S., & Sreedeep, S. Wilting characteristics of *Phaseolus vulgaris* and *Raphanus sativus* as a function of plant physiological and soil water retention parameters under the influence of fly ash-based water-absorbing polymer. Acta Geotechnica, Springer.