

मृदा भौतिकी पर्यावरण पर पूसा हाइड्रोजेल का प्रभाव तथा सोयाबीन-गेहूं फसल
चक्र प्रणाली में जल उपयोग प्रभावशीलता

**Effect of Pusa hydrogel on soil physical environment
and water use efficiency in soybean-wheat cropping
system**

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**DIVISION OF AGRICULTURAL PHYSICS
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Effect of Pusa hydrogel on soil physical environment and water use efficiency in soybean – wheat cropping system

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C E R T I F I C A T E

This is to certify that the thesis entitled, **“Effect of Pusa hydrogel on soil physical environment and water use efficiency in soybean–wheat cropping system”** submitted to the Faculty of the Post-Graduate School, Indian Agricultural Research Institute, New Delhi, in partial fulfillment of the requirements for the award of the degree of **Doctor of Philosophy in Agricultural Physics** is a record of *bona fide* research work carried out by **Mr. Bhaskar Narjary, Roll No. 9509** under my guidance and supervision, and that no part of this thesis has been submitted for any other degree or diploma. It is further certified that all the assistance and help availed during the course of investigation as well as all sources of information have been duly acknowledged by him.

Place: New Delhi
Date: April , 2011

(P. Aggarwal)
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“My first gift and my last, to you

I dedicate this fascicle of songs -

The only wealth I have:

Just as they are, to you”.



To,

My Respected Chairperson

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1. INTRODUCTION



India achieved significant production and productivity gains through technology driven farming during the mid 1960s to early 1990s. However, the need for improving the physical properties of soils to increase productivity in the agricultural sector was greatly felt in post green revolution era, where yields were stagnated in spite of heavy use of inputs such as water and fertilizer. Soil physical condition is one factor that can limit crop production. Poor soil physical condition can restrict water movement into the soil and its subsequent uptake by plant roots. Producers and researchers alike are interested in improving the physical condition of the soil to enhance crop production. These goals can be accomplished through the use of good management techniques. One such technique involves addition of amending materials to improve the soil physical condition. Such materials are called soil conditioners.

Various Polymeric soil conditioners such as VAMA, Krilium were developed for improving soil physical environment specially aggregate stability, infiltration rate, water retention capacity and aeration porosity of soil to create more porous and favorable environment for better root growth. Most of the studies with polymers were performed in the laboratory or greenhouse without consideration for the economics at the production level in large-scale agriculture. When the polymer is mixed into the soil at rates of about 0.1% by mass, it translates into amounts of 1000 to 4000 kg ha⁻¹. Such rates are obviously not economical for most uses. Moreover they had quite short life-span and hence they were rapidly withdrawn from the market.

The need for more arable land in view of increasing agricultural production has renewed interest in the development of novel soil conditioner materials with new methods and lower rates of application. Polymers such as polyacrylamide which proved to be more efficient at lower application rates revived interest in the field of synthetic soil polymers. In the early 1980's, water-absorbing polymers or hydrogels were introduced for agricultural use. These polymers do not possess linear chain structures as developed previously but here the chains are rather cross-linked to form a three-dimensional network. Depending on synthetic conditions, type and density of covalent bonds that form cross-links, these polymers can absorb up to 1000 times their weight in

pure water and form gels. Most of the hydrogels marketed for agriculture come from cross-linked polyacrylamides and cross-linked acrylamide-acrylate copolymers, as they remain active for a much longer time.

Although wheat–soybean is one of the most dominant cropping systems on the Vertisols of central India but in the trans Indo-Gangetic Plains (Inceptisols), where water table is declining, soybean-wheat system is emerging as an alternate to rice–wheat. Cultivation of durum wheat in winter season (November to April) has a considerable potential due to congenial climate, while soybean in rainy season (June to October) has witnessed a phenomenal growth in the last two decades. Besides including a legume (soybean) in sequence with a cereal crop (wheat), combined use of available organic sources along with chemical fertilizers may prove beneficial for long-term productivity and sustainability of the system. As the water is the major yield reducing factor for *kharif* and *rabi* crops, the hydrogel amendments may improve seedling growth and establishment by increasing water retention capacity of soils and regulating the plants available water supplies.

A number of studies had been conducted in past to evaluate the effect of soil conditioners on hydraulic properties and aggregation in soils but they were mostly confined to the laboratory and pot experiments. Moreover, most of these soil conditioners were organic linear chained polymers, had short life span and in some case their end products were poisonous. Since the newly developed Pusa hydrogel by the institute (I.A.R.I) has very high water retention capacity, forms water stable aggregates, has a life span of one year and on decomposition yields simple products, an attempt is being to evaluate its efficiency in field condition as well in different soil types. Most of all earlier studies reported that synthetic soil conditioner effective in retention of water but their water release pattern were not properly investigated and past studies were mainly based on effect of a given hydrogel on one soil type, but there is hardly any literature where comparison has been made on extent of modification in hydro physical properties among different soil types. Hence the effect of a given hydrogel application on soil water retention at different suctions and modification of water transmission

characteristics needs to be fully tested /explored before recommending them for further commercial use in agriculture and allied sectors.

Keeping in view the limitation of these aspects, the present study was planned with the following objectives.

1. To conduct a laboratory study to compare the distribution of water content in different soil types in relation to hydrogel applications.
2. To conduct a field study for characterising soil physical environment under variable rates of hydrogel along with other soil amendments.
3. To study the improvement in water use efficiencies and growth of soybean and wheat crops by application of hydrogel and amendments.

2. BACKGROUND



2.1 Research Area I (Objective I)

To conduct a laboratory study to compare the distribution of water content in different soil types in relation to hydrogel applications.

2.1.1 Hydrogels:

Gels forming polymers or insoluble water-absorbing polymers were first introduced for agricultural use in the early 1980's. These polymers possess chain structures which are rather cross-linked to form a three dimensional network. Cross-linking occurs when polymerisation is carried out in the presence of a small amount of a divinyl compound. Depending on synthetic conditions, type and density of covalent bonds that form cross-links, these polymers can absorb up to 1000 times their weight in pure water and form gels. Three main types of hydrogels (water absorbing) have so far been developed as agricultural polymers: (1) starch-graft copolymers obtained by graft polymerisation of polyacrylonitrile on to starch followed by saponification of the acrylonitrile units (2) cross-linked polyacrylates (3) cross-linked polyacrylamides and cross-linked acrylamide-acrylate copolymers containing a major percentage of acrylamide units. Most of the hydrogels marketed for agriculture claimed to remain active for a much longer time. Hence considerable attention has been paid in the last few decades to use hydrogels to create suitable environment for planting sandy and sandy calcareous soils. Application rates ranged between 6 and 200 kg fed⁻¹ (Tayel and El-Hady, 1981; Azzam and El-Hady, 1983; El-Hady, 1987a, b; Rasheed *et al.*, 1997; El-Hady *et al.*, 2002, 2003; Wahba, 2005a, b). It is expected that applying organic materials mixed with the proper hydrogel to the soil may be more effective and economic than using each of them alone (El-Hady *et al.*, 1995a, b; 2002; 2003).

2.1.2 Effects of hydrogel on water holding capacity:

The uses of alternative water holding amendments and irrigation methods will become more important over time, especially in regions in reduced water availability. Hydrogels may have great potential in restoration and reclamation projects where opportunity for irrigation is limited and thus storing more water available for plant

establishment. Flannery and Busscher (1982) reported that, the use of hydrogel increased the amount of available moisture in the root zone, thus implying longer intervals between irrigations. The water-holding capacity depends on the texture of the soil, the type of hydrogel and particle size (powder or granules), the salinity of the soil solution and the presence of ions. Hydrogels absorb and store water hundreds of times their own weight, 400–1500 g water per dry gram of hydrogel (Johnson, 1984a; Bowman and Evans, 1991). Cross-linked polyacrylamides hold up to 400 times their weight in water and release 95% of the water retained within the granule to growing plants. Johnson (1984b) found that, PAM (polyacrylamide) increased the available water of sandy soil and its extent effect depends on the kind of gel-conditioner. In the same direction, Azzam and El-Hady (1983) found that the total water holding capacity for sandy soil treated with 0.2% of anionic polyacrylamide gel-conditioner (PAMG) was three times that for untreated soil, but field capacity was ten times that of untreated soil. Johnson and Veltkamp (1985) found that the treated sandy soil with PAM gel-conditioner gave a good effect on the water storage at different tensions (suctions). The amount of water retained by the sandy soil at each matric suction over the range of 100–15000 cm water significantly increased with increase of the gel- conditioner concentration (Al-Omran *et al.*, 1988; Al-Darby *et al.*, 1992; and EL-Shafei *et al.*, 1994). Al-Darby (1996) and El-Shafei *et al.* (1994) found that the available water was increased exponentially with the increase of the gel-conditioner concentration.

However, the water-holding capacity drops significantly at sites where the source of irrigation water contains high levels of dissolved salts (e.g. effluent water) or in the presence of fertilizer salts (Wang and Gregg, 1989). The amount of water retained is also adversely affected by chemicals or ions (Mg^{2+} , Ca^{2+} , Fe^{2+}) present in the water (Johnson, 1984b). James and Richards (1986) suggested that these divalent cations develop strong interactions with the polymer gels and are able to displace water molecules trapped within the polymer. Taylor and Halfacre (1986) reported that the efficacy of the super absorbents decreased with an increase in water salinity, which leads to a reduction in their water holding capacity. Based on pot experiment study on sandy loam soil of Iran, Taban and Naeini (2006) reported that, hydration capacity of aquasorb gel is reduced as the electrolyte concentration and electrical conductivity is

increased. Increased electrolyte concentration in soil solution, through drying, may result in gel dehydration and water release at potentials greater than field capacity, which may be lost to drainage.

Based on laboratory experiment Bhardwaj *et al.* (2007) reported that, on sandy soil of Israel, water retained by the absorbents alone at low suction ranged between 200 and 500 kg kg⁻¹ of polymer; water retained by the polymers when mixed with sand ranged between 40 and 140 kg kg⁻¹. Water retained per kilogram of polymer increased with an increase in polymer concentration in the sand while undergoing desorption, but absorbed water decreased with polymer concentration during sorption, indicating an effect of hysteresis and absorption kinetics in the water absorption process.

2.1.3 Effects of hydrogel on saturated hydraulic conductivity:

Use of water absorbents in sandy soils from arid and semiarid regions could serve as an important tool in increasing water use efficiency and crop production. It has been postulated that adding polymers to sandy soils may improve water availability to plants, not only due to polymer swelling but also by decreasing the hydraulic conductivity of the sand, thus decreasing drainage of water below the root zone (Kazanskii and Dubrovskii, 1992; Al-Omran and Al-Harbi, 1998). Several studies reported that there is a high exponential decrease in saturated hydraulic conductivity (K_s) of coarse texture soils with the increase the gel conditioner concentrations (Al-Darby *et al.*, 1992; El-Shafei *et al.*, 1992 and 1994; Al-Darby, 1996). Khafagi and Al-Gosaibi (1990) found that a hydrogel called P₄ increased the hydraulic conductivity of the sodic calcareous soil. Polyacrylamide polymers have proven to be effective in increasing hydraulic conductivity in medium textured, crusting soils (El-Morsy *et al.*, 1991; Ben-Hur and Letey, 1989; and Malik and Letey, 1991). Bryan (1992) showed that application of anionic PAM at the concentration of 0.5 g kg⁻¹ of air-dried soil on several medium and fine-textured soils significantly ($P \leq 0.05$) increased saturated hydraulic conductivity. Al-Darby (1996) found that the calculated unsaturated hydraulic conductivity as a function of volumetric water content (K_θ) was decreased with increasing gel-conditioner (Jalma) rate.

On a sandy calcareous soil of Egypt, El-Hady and Sedera (2006) concluded that incorporating 1 kg organic matter mixed with 1 g of acrylamide hydrogel reduced hydraulic conductivity 43.5% as compared to control. More decrease in the values saturated hydraulic conductivity was obtained by increasing the application rate of the mixture of both components. Based on laboratory experiment on sandy soil of Israel, Bhardwaj *et al.* 2007 reported that, applying a hydraulic head of tap water initially caused a decrease in the hydraulic conductivity, explained by the decrease in the volume of the soil-absorbents mixtures, followed by a steady increase in hydraulic conductivity ascribed to drainage of water from the swollen polymer granules that led to an increase in the size of pores available for water flow. The subsequent increase in the hydraulic conductivity was ascribed to partial draining of the swollen polymer granules by the pressure exerted on the soil-polymer mixtures by the hydraulic head. It is postulated that when no external forces are applied to the polymer granules, the hydraulic conductivity of the sand-polymer mixture would remain low. Leaching the soil-absorbent mixtures with distilled water, simulating rainwater, increased the volume of the mixtures (due to polymer swelling) and decreased their hydraulic conductivity due to pore blockage by the swollen polymer grains. Paluszek and Zembrowski (2008) reported that, on a sandy loess soil, the saturated hydraulic conductivity in the soil surface layer showed a significant increase by $2.13 \text{ m}\cdot\text{day}^{-1}$ and $3.52 \text{ m}\cdot\text{day}^{-1}$ in the plots when agrohydrogel mixed with soil @ of $1 \text{ g}\cdot\text{kg}^{-1}$ and $2 \text{ g}\cdot\text{kg}^{-1}$ respectively. Based on two year study on a sandy soil of Egypt El-Hady *et al.* (2009) reported that, applying acrylamide hydrogels decreased the mean diameter of soil pores and in turns its water transmitting properties namely, infiltration rate, hydraulic conductivity and transmissivity for vertical flow of water through soil profile.

Based on pot experiment on different soil types (sand, loam, silt loam, sandy loam and clay soils) Hillary *et al.* (2010) reported that, super absorbent polyacrylate (SAP) hydrogel significantly increase plant available water content and evapotranspiration was reduced in eight of the nine tree species when soils are amended with 0.4% hydrogel. It is probable that soil amendment with SAP decreased the hydraulic conductivity of soil that might reduce plant transpiration and soil evaporation.

2.1.4 Effects of hydrogel on pore size distribution:

Pagliai *et al.* (1981) showed that application of sewage sludge and compost at the rate of 150 t ha^{-1} on a sandy loam soil significantly ($P \leq 0.05$) increased total porosity by increasing the number of pores (500-50 and 50-30 μm) and decreasing the number of pores larger than 500 μm . Synthetic polymers are effective in increasing hydraulic conductivity and porosity, improving the water holding capacity (Shanmuganathan and Oades, 1982). Helalia *et al.* (1992) showed that 2.5–15 g kg^{-1} dose of hydrogels Acryhope and Aquastore-B increased total porosity and the retention of useful water in sandy soils. According to Al-Darby (1996), addition of gel-forming soil conditioners (Jalma) to a sandy soil increased the percentage of micropores (5-30 μm) from 10.0 to 17.86 and decreased the diameter of the largest pore from 250 to 120 μm . On a sandy calcareous soil of Egypt, El-Hady and Sedera (2006) concluded that, soil conditioning by applying acrylamide hydrogels decreased the bulk density of the soil as well as the macroporosity (drainable pores having the diameter of $> 28.8 \mu$) relative to those of untreated soil. Sadegian *et al.* (2006) showed that application of polyacrylamide (PAM), pumice, and straw as synthetic soil conditioners on the 0 to 5cm layer of a sandy loam soil significantly ($P \leq 0.01$) decreased surface sealing by decreasing bulk density and increasing microporosity. On a sandy loess soil, Paluszek and Zembrowski (2008) reported that, the total porosity in the soils improved by agrohydrogel was significantly greater by $0.028\text{--}0.040 \text{ m}^3 \text{ m}^{-3}$ while compared with control plots. The addition of the polymer increased significantly the content of macropores with the diameter equivalent to $> 20 \mu\text{m}$ by $0.045 \text{ m}^3 \text{ m}^{-3}$ in the plots with the dose of 1 g kg^{-1} and by $0.054 \text{ m}^3 \text{ m}^{-3}$ in the plots with the dose of 2 g kg^{-1} . By contrast, the content of mesopores with the diameters ranged from 0.2 to 20 μm in the soils with the addition of hydrogel decreased significantly by $0.015 \text{ m}^3 \text{ m}^{-3}$ in comparison with the control. Based on laboratory experiment Asghari *et al.* (2009) reported that, addition of 0.25 and 0.5 g of polyacrylamide (PAM) on a sandy soil significantly ($P \leq 0.05$) increased the percentage of mesopores, as compared with the control, by decreasing macropores. Based on two year study on a sandy soil of Egypt, El-Hady *et al.* (2009) reveal that, applying acrylamide hydrogels decrease the bulk density of the soil as well as the macroporosity (drainable pores having the diameter of

> 28.8 μm) relative to those of untreated soil but shows opposite trend to that of macro porosity. The ratio between micro and macro pores is of great importance in revealing the rate of water retention and water movement in the soil. Incorporating the examined hydrogels into sandy soil beneficially modifies this ratio. While micro: macro porosity in the untreated soil was 0.27: 1, it increased by soil conditioning to be 0.55:1 and 0.76:1 due to the addition of 2 and 3 g hydrogel / plant pit respectively and to reach about 1:1 by addition of 4 g hydrogel to each plant pit of sandy soil, indicating slow water movement and more water retention in the soil.

2.1.5 Effects of hydrogel on Swelling:

Miller (1979) observed hydrolyzed starch-polyacrylonitrile graft polymer increased surface soil swelling and decreased infiltration rate of sandy soils. Based on a laboratory column study Al-Darby *et al.* (1996) concluded that the conditioner-gel particles were highly swollen upon water absorption resulted in large soil expansion.

2.2 Research Area II (Objective II)

To conduct a field study for characterizing soil physical environment under variable rates of hydrogel along with other soil amendments.

2.2.1 Effects of amendments and hydrogel on aggregate stability:

Aggregate stability, defined as the resistance of soil aggregates to failure when subjected to disruptive forces, provides an integral measure of the strength of intra-aggregate bonds. Coarse-textured sandy loam soils often are poorly structured. Water applied as irrigation or rainfall to these soils causes aggregate breakdown and resulted undesirable physical conditions because of their weakly bonded aggregates (Schjonning *et al.*, 1994; Nadler *et al.*, 1996; Imbue *et al.*, 2005). It leads to seal formation, decreased infiltration, and increased runoff (Sadegian *et al.*, 2006). Other problems of coarse-textured soils are low water and nutrient holding capacity because they contain more number of macropores (Sen and Bhadoria, 1987; Tester, 1990; Al-Darby, 1996; Nyamangara *et al.*, 2001). In order to eliminate or reduce these limitations researchers have proposed various methods for conditioning or strengthening these soils by the application of different natural or synthetic soil conditioners.

Intensive agriculture production is known to cause a decline in soil organic matter content, that leads to the alteration of soil structure stability. The addition of exogenous organic matter generally results in the improvement in soil organic matter content and soil stability (Metzger *et al.*, 1987). The effects observed on aggregate stability vary with the characteristics of both exogenous organic matter and the soil. The organic matter increases aggregate stability by the enhancement of aggregate hydrophobicity and the inter-particle cohesion.

Farmyard manure reduces dispersion in soil, there by increasing macro-aggregates in soil (Ray and Gupta, 2001). Chadravansi *et al.* (1999) reported that, increase in mean weight diameter (MWD) with addition of N or FYM was due to higher percentage of macro-aggregates in soil. Manure application improved aggregate stability, which might have been associated with increased SOC concentration and soil biological activities (Haynes and Naidu, 1998; Chadravansi *et al.* 1999; Aoyama *et al.*, 2000; Tripathi and Singh, 2004). Chaney and Swift (1986) found a high positive correlation between aggregate stability (measured by wet sieving) and SOM content in 26 agricultural soils with different properties. Aoyama *et al.* (1999a, b) also reported that long-term application of FYM increased SOC level and favored the formation of slaking resistant macro-aggregates (250–1000 μm), thereby increasing MWD. Based on eight year experiment Bhattacharyya *et al.* (2007) reported that, aggregate size distribution was significantly impacted by FYM addition, Proportion of aggregates >1 mm was 17–19% greater in soil receiving FYM over that receiving no FYM, whereas aggregates <1 mm decreased significantly in plots with FYM over that with no FYM. Increase in percentage of macro-aggregates and reduction in percentage of micro-aggregates with FYM application was likely due to conversion of some of the micropores to macropores as a result of cementing action of organic acids and polysaccharides formed during the decomposition of organic residues by microbial activity (Mishra and Sharma, 1997).

Levy and Miller (1999) indicated that, application of anionic PAM with a molecular weight of 107 Da on a sandy loam soil significantly ($P \leq 0.05$) increased mean weight diameter (MWD) of aggregates (wet sieving), as compared with the control. Nyamangara *et al.* (2001) reported that, addition of 37.5 t ha⁻¹ of cattle manure

on a sandy soil significantly ($P \leq 0.05$) increased water aggregate stability (WAS) by 2-10 mm. Shaviv and Sinai (2004) reported that, spraying LIMA polymer on a silty loam soil at the concentration of 5 g L^{-1} increased aggregate stability of the soil and reduced soil clogging. Asghari *et al.* (2009) reported that addition of 0.25 and 0.5 g of polyacrylamide (PAM) on a sandy soil significantly ($P \leq 0.05$) improved the soil structure (MWD and WAS) and consequently prevented surface sealing for 6 months, as compared with the control. Paluszek and Zembrowski (2008) observed a positive influence of Agro-HydroGel applied in doses of 1 g kg^{-1} and 2 g kg^{-1} on the aggregate structure of eroded Haplic Luvisols developed from loess. Aggregate size distribution in the 0–5 cm layer of Ap horizon found a significant decrease of the share of clods ($> 10 \text{ mm}$) when soils amended with hydrogel and an increase of the content of water-stable aggregates with a size of 0.25–5 mm and 0.25–10 mm.

2.2.2 Effects of management practices on soil temperature:

Soil temperature is agriculturally more significant than aerial temperature (Chaudhary and Prihar, 1974). Soil temperature is one of the most important factors that affect the soil water flux, soil heat storage, soil heat flux, seed emergence, nutrient uptake and plant growth. The functional activity of plant roots can be affected at both low and high soil temperatures. Most plant responses alter with changing temperature, with lower and upper threshold values and a prominent optimum (Pollock, 1990). The warmer soils speed up the crop emergence, increase the competitiveness with weeds and increase the livelihood of a good crop stand.

2.2.2.1 Soil organic matter and soil temperature

The soil rich in soil organic matter have a low reflection coefficient and therefore, stay relatively hotter during the day. The thermal conductivity of organic matter is considerably less than that of many soil minerals. Also, because organic matter promotes granulation (loose friable structure), it further reduces the thermal conductivity of soil (Van Duin, 1963).

2.2.2.2 Mulch and soil temperature:

Surface application of wheat straw at 7.5 t ha^{-1} reduced the maximum soil temperature from 37.1 to 28.6°C (Bragagnolo and Mielniczuk, 1990). The soil temperature was lower for all the layers under residue mulch (Kalra *et al.*, 1984). Straw

mulch lowering soil temperature and narrowing down diurnal temperature fluctuations in the top few inches of the soil have been reported by Moddy *et al.*, 1963. Further, Tomar and Verma (1985) reported that the mulching of paddy straw @ 5 or 10 t ha⁻¹ reduced fluctuations in soil and delayed all growth stages of early and late sown wheat.

An experiment conducted by Cook *et al.* (2006) to assess the effect of mulch on rainfall interception, soil physical characteristics and temperature under *Zea mays* L showed that soil temperature at 0.075 m depth was different mostly at the end of August and during early September and for the 0.15 m depth, temperature patterns were similar. For the organic mulches, temperature beneath wheat straw was lower than under FYM compost and the control and for the inorganic mulches, black matting and black polyethylene mulch usually had higher temperature than bare soil. In the same study, it was found that soil temperature at 0.15 m taken around 16:00 was significantly reduced by application of wheat straw mulches. Between 31 May and 7 August the heaviest application reduced mean temperature (18.7 °C) by 2.2 °C compared with the control and, as the amount of wheat straw increased, soil temperature was reduced. Readings taken in the morning showed a mean reduction of 2.8 °C for wheat straw rates of 4, 6 and 8 t ha⁻¹ compared to the control (no mulch) treatment. During the afternoon, reductions in soil temperature under the same wheat straw rates were as much as 2.8 °C lower compared to the control (no mulch) treatment.

2.2.3 Effects of soil amendments and synthetic soil conditioners on soil compaction:

Soil compaction is a major cause of soil degradation in most agricultural soils (Van Lynden, 2000). In a compacted soil, the particles are pressed together, thus reducing pore spaces which contain air and water necessary for good plant growth (Aina *et al.*, 1985). Application of polyacrylamide (PAM), pumice, and straw as soil conditioners on the 5 cm layer of a sandy loam soil significantly ($P \leq 0.01$) decreased surface sealing by decreasing bulk density and increasing microporosity (Sadegian *et al.* 2006). Conditioning effects of organic materials, in terms of increasing water holding capacity, modifying bulk densities and pore size distribution, are more pronounced for coarse-textured soils than for medium and fine texture soils (Nelson and Kladvik, 1979; Metzger and Yaron, 1987; Bauer and Black, 1992). Based on two year study on a

sandy soil of Egypt, El-Hady *et al.* (2009) reveal that, applying acrylamide hydrogels decrease the bulk density of the soil as well as the macroporosity (drainable pores having the diameter of $> 28.8 \mu\text{m}$) relative to those of untreated soil

2.3 Research Area III (Objective III)

To study the improvement in water use efficiencies and growth of soybean and wheat crops by application of hydrogel and amendments.

2.3.1 Effects of synthetic soil conditioners on plant establishment and growth:

Hydrogels, which were developed to increase water holding capacity of amended media, have been used to aid plant establishment and growth in dry soils. Plants grown in substrates amended with hydrophilic polymers were slower to wilt than those in unamended medium (Still, 1976; Conover and Poole, 1979; Gehring and Lewis, 1980; Baasiri *et al.*, 1986; Woodhouse and Johnson, 1991).

Hydrophilic polymers have been used to establish tree seedlings and transplanted in the arid regions of Africa and Australia to increase plants survival (Callaghan *et al.*, 1988; 1989; Save *et al.*, 1995; Specht and Harvey, 2000). Gehring and Lewis (1980) reported that, moisture stress of plants decreased by incorporation of a hydrophilic polymer into the medium. Wallace and Wallace (1986) have stated that, generally the most favourable results for seed emergence and water infiltration came from an anionic polymer where, a cationic polymer was less effective. Hydrogel amendment improved emergence of wheat (Saleh and Hussein, 1987), germination of maize pollen (El-Sayed and Kirkwood, 1992), and salt tolerance and growth of certain horticultural crops, including barley, tomato, cucumber and lettuce (Awad *et al.*, 1986; Szmids and Graham, 1990; El-Sayed *et al.*, 1991). Ahmed and Verplancke (1994) reported an improvement in germination and biomass production of trifolium, lettuce and ryegrass in dune sand with gel amendment. Seedling emergence rate and dry seedling weight in lettuce, tobacco and cotton increased in soil amended with hydrogel (Wallace and Wallace, 1986). Woodhouse and Johnson (1991) have shown varying degrees of improvement in the germination and establishment of different plant species.

Hydrophilic polymers usually have some effects on plant establishment, with the greatest benefit obtained when hydrophilic plants planted in dryer conditions. Fry and Butler (1989) observed that, *Festuca arundinacea* (Tall fescue) benefited from pre-seeding incorporation of hydrophilic polymers into the soil. The soil required large amount of hydrogel (greater than 1% of soil volume) to achieve a beneficial response from *Festuca arundinacea* in greenhouse. Survival rates of *Pyracantha coccinea* (scarlet firehorn) and *Rhododendron sp.* (azalea) were increased and dry weights were higher when hydrophilic polymer was incorporated into the medium (Bilerback, 1987). Drought sensitive plant, such as *Petunia parviflora* (petunia), responded well to the hydrogels in dry conditions and increased flower numbers and dry weights (Boartright *et al.*, 1997). Responses of moisture requiring plants to the hydrogels have been inconclusive and sometimes negative when used in field and container productions. In a container production of *Betula pendula* (European birch), hydrogel addition into the medium has shown the reductions in overall plant mass and the amount of water available in the plants due to presence of soluble salts in the medium (Tripepi *et al.*, 1991). Wang (1989) found that *Codiaeum variegatum* (croton), *Dieffenbachia sp.* (dumb cane) and *Hibiscus rostratus* (hibiscus) show no visible size difference when hydrophilic polymers were used compared to when they were not used. Specht and Harvey-Jones (2000) found that, less drought tolerant tree species had a much more favourable response to the incorporation of hydrophilic polymers. The survival rates of *Pinus halepensis* (Aleppo pine) seedling, adventitious root growth and overall plant mass was doubled in hydrogel treated soil compared to no hydrogel amendments (Huttermann *et al.*, 1990). *Pinus pinea* (umbrella pine or Italian stone pine) seedlings survived 1.4 to 2.0 times longer, with applications of hydrogels, compared to the trials with no hydrogels in the field production (Save *et al.*, 1995).

Silberbush *et al.* (1993a) tested the polyacrilamide (PAM) hydrophilic gel Agrosoak (0.00, 0.15, 0.30, and 45% by weight in the upper 25 cm of the soil) as a conditioner for corn (*Zea mays* L.). They indicated that the water storage capacity of the soil increased with the rate of Agrosoak. Yield component except shoot dry weight increased with the Agrosoak application rate. Also, Silberbush *et al.*, (1993b) tested the Agrosoak hydrogel for cabbage (*Brassica oleraceae* L.). They reported Agrosoak

increased water availability which indeed contributed to the increase in the yield of the crop irrigated with saline water. However, it was concluded that this particular PAM enriched the soil solute with sodium (Na^+) reducing the yield when irrigated with fresh water.

The effects of different cultivation methods with addition of either organic mulch or a hydrophilic polymer (aquasorb), on seeding emergence of seven indigenous plant species were evaluated in South Africa by Witbooi and Esler (2004). Seedling emergence was higher in areas where aquasorb was used.

The performance of the gel on plant growth depends on the method of application as well. It was shown that spraying the hydrogels as dry granules or mixing them with the entire root zone is not effective (Flannery and Busscher, 1982). Better results seem to be obtained when the hydrogels are layered, preferably a few inches below soil surface. However, generalizations should be avoided when interpreting results as a number of factors such as type of hydrogel, particle size, rate of application and type of plant has to be taken into consideration.

2.3.2 Effects of Soil amendments and synthetic soil conditioners on water use efficiency:

Water use efficiency reflects the relation between the production and the total seasonal water used *i.e.*, yield produced in kg by each cubic meter of water used. Water held in the expanded hydrogel is intended as a soil reservoir for maximizing the efficiency of plant water uptake. Mixing of super absorbent materials (hydrogel) as hydrophilic organic polymeric products with sandy soil increases the soils capacity to store water. The water stored in this way is available to plants for considerable time. Moreover, germination process, plant growth, nutrient uptake by plants and both water and fertilizer efficiency was beneficially increased by mixing the plant pits in sandy soil with hydrogels (El-Hady, 1987a; El- Hady and Wanes, 2006; El- Hady and Sedera, 2006; El- Hady *et al.*, 2009). There is other evidence showing that the presence of polymers prolongs the survival of plants (Callaghan *et al.*, 1988; Woodhouse and Johnson, 1991), and increases water use efficiency and dry matter production during periods of drought (Azzam, 1983 and 1985; Woodhouse and Johnson, 1991).

Allahdadi *et al.* (2005) studied the impact of Superab A200 on drought stress of soybean (*Glycine max L.*). In this field trial, the different rates of Superab A200: 0.75, 150 and 225 kg ha⁻¹ were obtained along with irrigation intervals of 6, 8, and 10 days on yield and yield components and some physiological characteristics of soybean. The results showed that the highest yield and yield components obtained from 6 days irrigation interval and 225 kg ha⁻¹. The number of pod per main stem and branches, percentage of seed oil and nodule dry weight were increased with application of 150 kg ha⁻¹ Superabsorbent polymer (SAP). Also, the longest irrigation interval without application of SAP produced the lowest yields and yield components.

Based on two year study in Egypt, El-Hady and Camilia (2006) reported that, on a sandy calcareous soil water use efficiency of tomato plant were increased 18.8 and 33.6% for compost as compared to control when compost were applied @ 1 kg and 2 kg per plant pit, respectively and 22.9 and 36.2% when mixture of anionic and cationic hydrogel was applied @2 and 4 g G/plant pit were respectively. The combined effect of both types of soil conditioners on water or fertilizers use efficiency were 1.3, 1.43 and 1.65 times that of untreated soil by incorporating 1 kg compost mixed with 1 g G; 1 kg compost mixed with 2 g G and 2 kg compost mixed with 1 g G in the plant pit, respectively.

3. MATERIALS AND METHODS (GENERAL)

In order to achieve the objectives of present investigation, a column study was carried out in the laboratory of Division of Agricultural physics, IARI. Besides, field experiments on soybean-wheat cropping system were conducted during the *kharif* (July-November) season of 2009 and 2010 and *rabi* season (November -April) of 2009-10 at the research farm of Indian Agricultural research Institute, New Delhi. The details of the materials and methods adopted during the course of investigation have been presented in this chapter.

Materials and Methods

3.1 Details of laboratory experiment

A laboratory experiment was conducted to compare the effects of hydrogel on soil hydraulic properties (water retention, saturated hydraulic conductivity, swelling properties, and distribution of water content in the soil profile) of different soil types packed in PVC columns of 15 cm diameter and 50 cm length. Four different types of soil namely red sandy loam, black clay soil, sandy soil and alluvial sandy loam were collected from Block: Simlapal, Dist: Bankura, West Bengal; NRC for Groundnut, Junagarh, Gujarat; Block: Baswa, Dist: Dausa, Rajasthan and MB 4C of research farm of Indian Agricultural Research Institute, New Delhi, respectively. Four compaction levels were fixed at 1.4 Mg m^{-3} and 1.6 Mg m^{-3} for black and sandy soil and 1.55 and 1.5 Mg m^{-3} for red and alluvial sandy loam soil, respectively.

3.1.1 Soil characteristics of sample collection sites

The Red soil belongs to Simlapal block of Bankura district in West Bengal which situated in red-laterite zone having undulated terrain in the family of Ustic Paleustalfs. Climatically red and lateritic Zone is within tropical dry sub-humid having rainfall ranging from 1100 to 1400 mm and Temperature maximum 45°C and minimum 10°C normally. The region was primarily undulating with mounds and valleys and exhibiting different grades of laterisation process in soil formation. Soils are well drained, susceptible to soil erosion due to rapid external drainage or run off, soil reaction ranges from acidic in ridges and near neutral in valleys. Organic carbons Content, phosphate are low. The texture class of soil was sandy loam. Alluvial soil

belongs to order Inceptisols and family of Typic Haplustept. The texture is sandy loam. The clay fraction consists of smectite (<50%), illite (<30%) and kaolinite or chlorite (<20%). The cation exchange capacity is less than 30 meq/100g and organic carbon less than 0.5%. The sandy soil belongs to Baswa block of Dausa district in Rajasthan. Climatically this region located tropical arid having rainfall ranging from less than 400 mm and Temperature maximum 50°C and minimum 10°C normally. This sandy soil belongs to family of Typic Torripsamment. The black soil belongs to Research farm of National Research Center for Groundnut of Junagarh district in Gujarat. The texture is clay. In the clay fraction there is dominance of fine smectitic clay. The black soil belongs to family of Typic Haplustert. The site characteristics and their physico-chemical characteristics were presented in table 3.1a and 3.1b.

3.1.2 Preparation of soil columns for maintaining different compaction and moisture levels

The top 15 cm of soils collected from the field was air dried and ground to pass through 2 mm sieve. Before filling the soils, PVC columns were closed at the bottom end and a rubber tube were attached near the bottom of column to drain excess water (if any) reaching the bottom. Air dry soils were filled in columns in 3-4 cm thick layers and was then compacted by applying appropriate blows of hammer (5 kg mass and diameter slightly less than the diameter of the columns) to get the desired bulk density levels. Two rates of Pusa hydrogel i.e., 0.7% and 0.5% by weight were mixed with the upper 10 cm soil layer of each type soils. Soil columns were initially saturated by applying 5 cm of water on the surface and soil moisture samples in quadruplicate were taken from 0-15 and 15- 30 cm soil layers on 4, 7, 14, and 22 days after watering (DAW) using a core.

Pan evaporation from an identical column filled with water instead of soil was measured daily to monitor the daily evaporation.

3.2 Field Experiments:

3.2.1 Location of the Experimental Site

The present study was carried out in the experimental farm of Indian Agricultural Research Institute (IARI), New Delhi located at 28°35' N latitude, longitude of 77°12' E and at an altitude of 228.16 m above mean sea level. The field had a fairly leveled topography.

3.2.1.1 Climate

The climate of the research farm is semi-arid with dry hot summer and cold winters. May and June are the hottest months with mean daily maximum temperature varying from 40 to 46° C, while January is the coldest month with mean daily minimum temperature ranging from 6 to 8° C. The mean annual rainfall is 710 mm, of which 80 per cent is received during southwest monsoon from July to September and the rest is received through 'Western Disturbances' from December to February. Air remains dry during most of the part of the year. The mean wind velocity varies from 3.5 km hr⁻¹ during October to 4.3 km hr⁻¹ in April. Mean daily values (during different weeks) of meteorological parameters recorded at the I.A.R.I. meteorological observatory adjoining to the experimental site during the *kharif* and *rabi* season are presented in Appendix I, II and III and is depicted in Fig. 3.1a, 3.1b and 3.1c.

3.2.1.2 Soils:

The soil of the experimental site belongs to the major group of Indo-Gangetic alluvium. The soil texture is sandy loam and belongs to Holambi Series, which is a member of non-acidic mixed hyperthermic family of Typic Haplustept, with medium to weak angular blocky structure. The soil is non-calcareous and neutral in reaction. Some of the physical and physico-chemical properties of the soils were determined are given in the table 3.2a and 3.2b.

3.2.2 Details of field experimentation

Field experiments were conducted at IV C field of main block of research farm of Indian Agricultural Research Institute during *kharif* 2009 and 2010 season for soybean (*Glycin max* L.) variety: DS-9814 and *rabi* 2009-10 season for wheat (*Triticum aestivum* L.) Variety: PBW-502.

For *kharif* experiment, main treatments consisted of three types of amendments *i.e.*, tank soil (TS), no amendments (NA) and farmyard manure (FYM) and sub-treatments consisted of three rates of hydrogel application *i.e.*, 5 kg ha⁻¹ (5G), 2.5 kg ha⁻¹

¹ and 0 kg ha⁻¹. Altogether there were nine (9) treatments in a split plot design with three replications (Table 3.3) in plots of 6 m long and 5 m wide. In tilled plots tillage was done in East-West direction only (Fig.3.2).

For *rabi* experiment, amendments were not applied in the main treatment plots and they were kept as such to study the residual effect of amendment applied in the previous season. However, the sub treatments imposed were similar to those of *khariif* season.

3.2.2.1 Preparation of seed bed:

Both FYM and tank soil were incorporated in upper 15 cm of soil 7 days before the sowing with the help of hand spade. Desired rate of hydrogel was mixed with 1 kg of dry sand and applied in rows at 5-7 cm soil depth along with seeds by using a manually drawn seed drill so as to cover the entire plot.

3.2.2.2 Intercultural Operations

3.2.2.2.1 Fertilization:

Before sowing fertilizer doses of 30 Kg N, 60 Kg P₂O₅ and 40 Kg K₂O ha⁻¹ were applied as basal doses along the lines in soybean for better growth.

Fertilizer doses of 120 Kg N, 80 Kg P₂O₅ and 60 Kg K₂O ha⁻¹ were applied in wheat for better crop growth. Half of N as urea plus full dose of P₂O₅ and K₂O as single superphosphate and muriate of potash were applied as basal dose just before sowing in the furrows. The rest of the N (as urea) was applied as top dressing in two installment, one at 35 days after sowing (DAS) and another at 70 DAS.

3.2.2.2.2 Irrigation:

In the *khariif* season two irrigation was given in first season (2009) and in the second season (2010) no irrigation was given as the in that period total 749 mm rainfall occurred in a 5-6 days interval.

In *rabi* season, total five (5) irrigations were given throughout the growing period of wheat (2009-10). The irrigation schedules are given below:

- 1st irrigation: (21 DAS)
- 2nd irrigation: (49 DAS)
- 3rd irrigation: (85 DAS)
- 4th irrigation: (109DAS)

5th irrigation: (121DAS)

3.2.2.2.3 Tillage:

In the *kharif* season of soybean (2009 and 2010), one disking was done followed by two cultivation with the help of cultivators only up to a depth of approximately 15-20 cm. In *rabi* season of wheat (2009-10) no disking was done, only upper few cm soils were disturbed by ploughing manually using a spade to maintain the same layout without disturbing the plots which existed in *kharif* season, so that the residual effects of amendments applied in *kharif* on succeeding *rabi* crop could be observed.

3.2.3 Observations

During the period of study, observations were taken on soil and plant parameters at desired intervals and are described below.

3.2.3.1 Leaf area index (LAI)

Field measurements of LAI were carried out in using LAI-2000 Plant Canopy Analyzer (LI-COR, USA), which is based on ‘fish-eye’ measurement of diffuse radiation interception by measuring gap fraction at five zenith angles (0-13, 16-28, 32-43, 47-58, 61-74°) simultaneously. The measured gap-fractions are inverted to obtain the effective LAI and the instrument was set to take four below and one above canopy measurements to estimate the LAI. Three LAI readings were recorded in each plot and two to three such readings were averaged out to represent the field LAI.

$$LAI = \frac{\text{Measured leaf area per plant (cm}^2\text{)}}{\text{Ground area covered by the plant (cm}^2\text{)}}$$

3.2.3.2 Biomass production

Three randomly selected plant samples (above ground) were taken and oven dried at 80°C for 48 hours for constant weight in order to estimate the accumulation of dry matter in to different parts (leaves and stems).

3.2.3.3 Seed yield

Plants from one square meter area each were cut above ground from three randomly selected places in each plot. After sufficient air drying, these samples were weighed. Threshing was done separately and seed weight was recorded. The average seed yield was reported.

3.2.3.4 Water use efficiency (WUE):

$$WUE = \frac{\text{Biomass produced (kg ha}^{-1}\text{)}}{\text{Amount of water used (mm)}}$$

3.2.3.5 Measurement of rooting characteristics

3.2.3.5.1 Root sampling:

For taking root samples a root auger of 10 cm diameter and 15 cm height was used. Root samples were taken for 0-30 cm of soil profile at 15 cm interval at flowering stage in both *kharif* and *rabi* season for treatments. Root samples at center were taken from center of row by placing the core auger such that center of core coincided with the base of cut plant. Similarly root samples at left were taken just adjacent to the left of center samples and root samples at right were taken just adjacent to the right of center samples.

3.2.3.5.2 Root washing:

The root samples were soaked over night in water containing sodium hexametaphosphate in small amount in a pail (Aggarwal and Sharma, 2002). The water on the top with floating roots was decanted into another container. Roots were then separated by carefully passing the decanted water over a fine sieve. The procedure was repeated 3-4 times for complete separation of roots from soils. Then the roots were air-dried so as to make the root samples ready for scanning.

3.2.3.5.3 Scanning and Image analysis using RHIZO system:

The scanning system: The scanner of RHIZO system had two light sources, one below the scanner glass called flat bed or reflective and one above it (in the scanner cover) called transparency unit or TPU. For root morphological measurements TPU lighting system was used for scanning. The light rays from TPU passed through the sample and then to the camera sensor below the scanner glass. The resulting image was sharp and clear with well-contrasted silhouette.

The image analysis system: RHIZO system acquires a direct digital (grayscale) image from the scanner and then created two other types of images for its analysis. One type of the image created was termed as 'Pixels classification image' in which all parts of the original image that fell below a user defined threshold of grayscale value were removed. The image had only two intensities black for pixels

belonging to roots and white for pixels belonging to the background. Another created image was termed as skeleton image, which consisted of a line, one pixel in diameter, which was superimposed over the earlier root image. RHIZO system measured the root length by scanning the length of the root skeleton. The colour of the skeleton indicated the diameter classification.

3.2.3.5.4 Root length density (RWD) and root surface density (RSD):

A root auger (0.15 m high and 0.10 m in diameter), was used to collect the root samples in the given soil mass at most active growth stage (70 DAS for soybean and 90th DAS for wheat). After removing the above ground biomass for determination of leaf area, the soil surface was cleaned of unwanted plant materials. The auger was placed on soil so as to keep the base of the stem at the centre, and pushed vertically for each 0.15 m layer down to 0.30 m depth. After the excavation, the soil cores were sealed in polythene bags, brought to the laboratory, washed, processed and length, surface of the volume of root were determined expressed as root length / root surface per unit volume of sampling core.

3.2.3.6 Soil moisture observations:

Soil moisture (0-90 cm) was determined from 15 cm depth intervals (0-15, 15-30, 30-45, 45-60, 60-75 and 75-90 cm) at every irrigation cycle for both the seasons (*kharif* and *rabi*) using screw auger and tube auger. The fresh samples were kept in tight aluminum containers to avoid any moisture loss during sampling and before weighing. Samples were weighed and oven dried at 105⁰ C for more than 48 hrs to attain constant weight. Dry weight and cane weight were also taken to calculate gravimetric moisture content and the soil moisture values were converted to depth units by multiplying with the bulk density (BD) of the respective zone. Depletion rates were calculated and reported as cm day⁻¹. The cumulated depletion was calculated during the entire crop growth period and used to determine water use efficiency.

$$\text{Gravimetric moisture content } (\theta_w) (\%) = \frac{A-B}{B-C} \times 100$$

Where, A= Weight of soil + cane box (g)

B= Weight of oven dried soil + cane box (g)

C= Weight of cane box (g) empty

Volumetric moisture content (%) (θ_v) was calculated by:

$$\theta_v (\%) = \theta_w \times \text{Bulk density}$$

3.2.3.7 Soil bulk density:

Soil bulk density (BD) was determined by using core auger method. For this purpose, a core cutter of 5.5 cm diameter and 15 cm height was used. Core cutter held an assembly of a sectional cylinder (core) of 6 cm diameter and 6 cm height with 2 rings of same diameter but 2 cm height on either side of it and was screwed to the collar of sampler (2.5 cm high) from the upper side. Collar of the cutter was attached to a galvanized thick hollow iron rod of nearly 85 cm height. The other end of the rod was attached to a handle. The bottom part of the cutter had a sharp edge and nearly 2.5 cm of the bottom portion of core cutter was slightly bent inward, hence the inner assembly remained above 2.5 cm from bottom part of cutter.

For taking samples, the assembled core cutter was positioned over the lines where hydrogel was applied and pressed inside the soil by rotating the handles or by dropping a hammer over the center portion of the upper end of the thick rod until the edge of the collar came to rest over the soil surface. Core cutter was then moved back and forth to loosen the soil grip around it. It was then slowly pulled out of the hole. After unscrewing the cutter from the collar, the unit of sectional cylinder with rings on each side was taken out carefully. Rings with undisturbed soil were used in pressure plate and determination of maximum water holding capacity. Cores with field soil were dried to 105°C in the oven and weighed. Bulk density (g cm^{-3}) of soil was calculated from the formula:

$$BD = \frac{(X - Y)}{V}$$

Where X = Weight of core with oven dry soil (g)

Y = Weight of core (g)

V = Volume of core (cm^3).

3.2.3.8 Soil Aggregate Analysis

Soil samples from each treatment were taken from the lines where hydrogel was applied after the harvest of crop and prepared in the laboratory by carefully braking

larger clods (field moist soil) by hand into smaller segments along natural cleavage and then air dried. Air dried samples were then passed through an 8 mm sieve and retained on a 4 mm sieve. The aggregates were then wet-sieved through a collection of 5 no. of sieves (4, 2, 1, 0.5, 0.25 and 0.1 mm size) following the procedure as laid out by Yoder (1936). The aggregates retained on each sieve were transferred to a set of pre-weighed beakers, oven-dried at 60⁰C for 24 hours and weighed. The mean weight diameter (MWD) was calculated as an index of aggregation (Van Bavel, 1949) along with other indices as follows:

- Macro- and micro-aggregates:

The line between macro- and micro-aggregates is commonly drawn at 0.25 mm (Edwards and Bremner, 1967; Oades and Waters, 1991). In our study, the macro-aggregate was determined by adding the aggregates retained over 4, 2, 1, 0.5 and 0.25 mm.

- The Mean Weight Diameter (MWD) of aggregates (Kemper and Roseneau, 1986):

$$\text{MWD} = \sum x_i w_i$$

Where, w_i is the proportion of aggregates retained over the sieves in relation to the whole, x_i the mean diameter of the class (mm).

- Structure coefficient (C_r): The ratio of the percentage of the total amount of fractions greater than 0.25 mm in diameter to the percentage of fraction having the diameter less than 0.25 mm (El-Shafei and Ragab, 1976).

3.2.3.9 Water retention characteristics:

Pressure plate apparatus (Soil Moisture Equipment Corporation, USA) method was used for obtaining soil water retention curve (Klute, 1986). It consists of a pressure chamber in which saturated soil samples (disturbed or undisturbed) are placed on porous ceramic plate through which the soil solution or air can pass easily but not the soil particles. As soon as the air pressure inside the chambers is raised above the atmospheric pressure, excess water is released until the equilibrium is attained. At this point moisture content of soils is measured gravimetrically which refers to the moisture content at the applied pressure.

Water retention by undisturbed soil core samples at 0, 10, 50, 100, 300, 500, 700 and 1500 kPa were determined. The pressure plates were saturated for overnight and undisturbed soil samples (cores) were placed on plate. Then water was added to saturate the sample and kept for 24 h for complete saturation. Saturated plates containing soil samples were placed in pressure chambers and desired pressures were applied. For attaining equilibrium it was kept for 48 h at the specified pressure. Then, samples were taken out from the chambers after they reached to equilibrium and the weights of soils were recorded. Following oven drying at 105-110°C till constant weight was attained, the dry soils were recorded. The moisture content retained by each sample at specified potential was determined from the moist and dry weight as recorded.

3.2.3.9.1 Pore Size Distribution

The effective size of pores was calculated from the following equation (Marshall *et al.*, 1996):

$$r = -\rho_w g h = -\frac{(2\gamma \cos \alpha)}{\psi}$$

where r is the mean equivalent cylindrical radius of pores (m) at a given matric potential ψ (Pa); γ the surface tension (72.75 mJ m⁻² at 20°C); α the contact angle between the water and pore wall, assumed to be zero); ρ_w the density of water (0.9982 Mg m⁻³ at 20°C); g acceleration caused by gravity (9.80 m s⁻²); and h matric suction or pressure head (m) applied just to drain the water. In our study, we grouped the pores into transmission pores ([P_T] 30 to 150 µm diameter corresponding to 0.2-1 m of water), storage pores ([P_S] 0.2 to 30 µm diameter corresponding to 1-150 m of water) and residual pores ([P_R] <0.2 µm diameter representing water retained at >150 m matric suction) as suggested by Greenland (1981).

3.2.3.9.2 Pore median diameter:

$$dm(\mu m) = \frac{300}{\Psi(kPa)}$$

Where d_m = the absolute matric potential at the mid-point (p) between the two limits of the soil moisture characteristics curve.

3.2.3.9.3 The moisture mid-point (p) = $\frac{(\theta_s + \theta_r)}{2}$

Where θ_s = saturated soil water content, and θ_r = residual soil-water content, when θ approaches its permanent wilting value.

3.2.3.9.4 Water release index:

$$I_m = \frac{d\theta}{d\psi(p)}$$

The water release index [I_m {(v/v) % / kPa}] is referred as the differential water capacity at the mid-point between the limits of the soil-water retention curve. This represents the amount of water release per unit change in soil matric potential around the mid-point (p).

3.2.3.9.5 Available water capacity (AWC) was calculated as the difference between soil water content at 20/30 kPa and 1500 kPa soil water suction.

3.2.3.9.6 Readily available water capacity was calculated as the difference in moisture content at 10 kPa and 100 kPa soil water suction.

3.2.3.10 Penetration Resistance:

In all the treatments along the lines where the hydrogel was applied at different moisture content soil penetration resistance (PR) was measured using Rimik cone penetrometer (model no. CP20). The maximum value of PR, which this instrument could measure, was 5000 kPa; maximum depth of penetration was 600 mm, as measured by an ultrasonic transducer. The diameter of the base of cone, and the slant height was 12 and 24 mm and angle of cone was 30°. The capacity of load cell was 60 kg. The instrument had a data logger system attached to it for automatic recording of data in the field. Retrieval of data on PC using CP20V2 software gave the recorded PR data at an interval 15 or 20 mm soil depth in graphical as well as tabular form (details may be obtained from the hardware manual of ‘Rimik cone penetrometer CP20’).

3.2.3.11 Soil temperature:

Soil temperature from each treatment at 0, 5, 10 and 15 cm were recorded by using digital thermometer. The soil temperature was recorded at drier and moist state in all the treatments during *kharif* season and at hourly interval during *rabi* season in hydrogel treatment plots with no amendment application.

3.2.3.12 Saturated hydraulic conductivity (K_s):

The constant head test with the permeameter is one of the most commonly used methods for determining the saturated hydraulic conductivity of soils in the laboratory. The samples were taken in cores after the harvest of crop with the help of core auger. This procedure allows water to move through the soil under a steady state head condition while the quantity (volume) of water flowing through the soil specimen is measured over a period of time. The test operates in accordance with the direct application of Darcy's law to a soil liquid configuration representing a one-dimensional, steady flow of a percolating liquid through a saturated column of soil from a uniform cross-sectional area. In this method, a cylindrical soil sample of cross-sectional area A and length L is placed between two porous plates that do not provide any extra hydraulic resistance to the flow. A constant head difference, $H_2 - H_1$, is then applied across the test sample. By measuring the volume V of the test fluid that flows through the system during time t , the saturated hydraulic conductivity K_s of the soil can be determined directly from Darcy's equation:

$$K_s = \frac{VL}{At (H_2 - H_1)}$$

Where; K_s = Saturated hydraulic conductivity (cm day^{-1})

A = Cross sectional area of the core

t = Time of water flow

$H_2 - H_1$ = Hydraulic head difference

V = Volume of water flow during t

L = length of the core

3.2.3.13 Field saturated hydraulic conductivity (K_{fs}):

Saturated Hydraulic Conductivity in field was measured by Guelph permeameter which is a constant head well permeameter (Reynolds, 1993, Reynolds *et al.*, 2002) consisting of a mariotte bottle that maintains a constant water level inside a hole augered in the soil. The method involves measuring the steady-state rate of water recharge into the soil from a cylindrical well hole, in which a constant depth (head) of water is maintained. The analysis of steady-state discharge from a cylindrical well in unsaturated soil, as measured by the Guelph Permeameter technique, accounted for all

the forces that contribute to three dimensional flow of water into soils: the hydraulic push of water into soil, the gravitational pull of liquid out through the bottom of the well, and the capillary “pull” of water out of the well into the surrounding soil.

Equation for one-head analysis for K_{fs} :

$$K_{fs} = \left[\frac{CQ}{2\pi H^2 + \pi a^2 C + 2\pi H/\alpha} \right]$$

Where;

K_{fs} - Field-saturated hydraulic conductivity (entrapped air present), in cm sec^{-1} .

R - Steady state rate of fall of water in the reservoir tube of the permeameter, in cm sec^{-1} .

Alpha parameter (α) - slope of the natural log of K – Q curve = 0.12 cm^{-1} for most of agricultural soils, H - Well height in cm, a - Well radius, in cm,

Q = XR, where X - reservoir constant = 35.43 cm^2

C-Factor a numerically derived shape factor, dependent on the well radius and head H of water in the well.

3.2.3.14 Soil texture:

International pipette method (Kilmer and Alexander, 1949) was used to determine sand, silt and clay percentage for each sample. USDA textural triangle was used to determine textural classes.

3.2.3.15 Soil Organic carbon:

Determination of organic was carried out by using titration method (Walkley and Black, 1934). In this method organic matter is oxidized with chromic acid (potassium dichromate + H_2SO_4) and the unconsumed potassium dichromate is back titrated against ferrous sulphate or ferrous ammonium sulphate (redox titration).

3.2.3.16 Maximum water holding capacity and saturation %:

Maximum water holding capacity was determined by core ring method (Singh, 1989). The undisturbed soil samples were taken from the field in the cores with the help of a core sampler. The upper core ring was used for determination of maximum water holding capacity of undisturbed soil. Any protruding soil was trimmed with a knife. A piece of filter paper was held to the bottom of the core with a cheese cloth and rubber

band. Cores were then placed in the pans provided with sufficient water to reach upon the brim of the cores and saturate for 48 hours.

After saturation core rings were removed from the plate and drained for 30 minutes and saturated weight was taken and then samples were kept in oven for drying. After 48 hours dry weight of the samples was also measured.

$$M.W.H.C(\%) = \frac{\text{Maximum water absorbed by the soil} * 100}{\text{Oven dry wt. of the soil}}$$

Statistical analysis

The design of the experiment was split plot design. Statistical analysis of laboratory as well as field data was done by using the software MSTAT_C.

4. RESULTS

4.1 RESEARCH PAPER I



Water availability in different soils in relation to hydrogel application

4.1.1 Abstract

Laboratory study was conducted in PVC columns to investigate the effect of application of hydrogel in modifying the hydraulic properties of different soil types. The main treatments consisted of four different soil types viz. sandy, alluvial sandy loam, red sandy loam and black clay, and sub-treatments with three levels of gel application *i.e.*, 0.7, 0.5 and 0%, mixed with upper 10 cm of soil. In all the soil columns, 5 cm water was applied and samples were taken with a core auger on 4th, 7th, 14th and 22nd days after watering (DAW). The undisturbed soil of the rings of the core assembly was used for generating soil water retention curve and soil of the core was used for determining saturated hydraulic conductivity (K_s), bulk density and soil water content.

Results of SWC during drying showed that in sandy soil with gel application @ 0.7%, the water release rates were relatively uniform throughout the entire drying period, whereas in black clay soil, these were faster initially (4-7 DAW) but reduced to < 0.5% per day thereafter.

The result of soil water characteristic curve revealed that water release per unit suction change in 0-10 kPa range (unavailable to plants) under no gel was higher as compared to soil with gel except in alluvial soil where these rates were similar. However water release in 10-100 kPa range (plant available water) was significantly lesser in soils without hydrogel as compared to gel treatment in all the soil types. Results thus indicated application of hydrogel significantly improved the readily available water capacity (RAWC). The water release per unit change in suction became very less at >100 kPa for all the soil types and hence, 100 kPa could be considered as the critical limit of soil water potential beyond which water availability became restricted. Gel application increased mid point moisture (MPM) and reduced median pore diameter (d_m) and moisture release index (I_m), which confirmed the efficacy of gel in improving RAWC.

Drying pattern of soils showed that under low evaporative condition, for red sandy loam, alluvial sandy loam, sandy and black clay, critical SWC under 0.7% gel treatment reached at 7, 14, 22 and 4 DAW, respectively. The above results thus clearly indicated that gel is better suited for sandy soil since, it improved the water availability for a longer period which corresponded with irrigation interval for most of agricultural crops, whereas, it was found less effective in black soil where critical soil water content reached early (4-7 days).

Key words: Alluvial soil, black soil, hydrogel, RAWC, red soil, sandy soil.

4.1.2 Introduction:

Research on the use of soil conditioners is getting more attention in last two decades especially in regions where water resources are scarce. Synthetic soil conditioners promote aggregate stability by gluing particles together within aggregates as well as by coating aggregate surfaces (Shainberger *et al.*, 1990). They also have great potential in restoring soil productivity where opportunity for irrigation is limited. It was found that the water storage at different tensions is improved significantly in sandy soil treated with gel-conditioner (Choudhary *et al.*, 1995; Huttermann *et al.*, 1999; Yangyuoru *et al.*, 2006; Abedi-Koupai *et al.*, 2008). It was also reported that the use of hydrogel increased the amount of available moisture in the root zone causing longer intervals between irrigations (Flannery and Busscher, 1982; Sharma, 2004; Abedi-Koupai *et al.*, 2004; Allahadi *et al.*, 2005; El-Hady *et al.*, 2009). Cross-linked polyacrylamides hold up to 400 times their weight in water and release 95% of the water retained within the granule to growing plants (Johnson, 1984a; Bowman and Evans, 1991). It has been postulated that adding polymers to sandy soils may improve water availability to plants, not only due to polymer swelling but also by decreasing the hydraulic conductivity of the sand, thus decreasing drainage of water below the root zone and also by increasing retention pores (Kazanskii and Dubrovskii, 1992; El-Shafei *et al.*, 1992; Al-Darby, 1996; Al-Omran and Al-Harbi, 1998; El-Hady and Sedera, 2006). The effect of addition of different concentrations of highly cross-linked polyacrylamide in sandy soil, on the survival of pine seedlings during water stress was investigated by Huttermann *et al.* (1999). The highest addition of 0.4% increased the

water retention and also increased the change in water potential of soil per unit change in soil water content.

In few studies contrasting results have been reported. Leciejewsk (2009) observed that in sandy loess soil treated with hydrogel, soil water storage was increased mainly in the range of pF less than 2 *i.e.*, it enhanced macro pores but micro pores were unaffected. These results were similar to those reported earlier by Paluszek and Zembbrowski (2008). In few other reports it was mentioned that hydrogel application in sandy soils significantly increased water retention capacity (Huttermann *et al.*, 1999, Abedi-Koupai and Sohrab, 2004), while in loam and clay soils the effect was negligible. Hence, in soils of different types *i.e.*, red, black, sand and alluvial, the effect of hydrogel application on soil water retention at different suctions and modification of water transmission characteristics needs to be fully explored before recommending them for further commercial use in agriculture and allied sectors.

Thus, the objective of this study was to determine the effectiveness of a hydrogel in improving water availability in different soil types by studying their hydraulic characteristics.

4.1.3 Material and Methods:

The study was conducted in laboratory of Division of Agricultural Physics, Indian Agricultural Research Institute during August and September months in 2010. The four different types of soil used for the study were- red sandy loam soil from Simlapal Block in Bankura district, West Bengal; Black clay soil from research farm of National Research Center for Groundnut, Junagarh, Gujarat; Sandy soil from, Baswa block, Dausa district, Rajasthan; Alluvial sandy loam from research farm of Indian Agricultural Research Institute, New Delhi. Soil samples for each soil type were collected from 0-15 cm soil layer. Further description of these soils is presented in Table 3.1a and 3.1b (see Material and Methods, Chapter 3).

4.1.3.1 Preparation of soil columns:

The soil samples were air dried and ground to pass through 2 mm sieve. PVC columns of 50 cm height and 15 cm diameter sealed at the bottom were used for carrying out the laboratory study. A rubber tube was attached near the bottom of column to drain excess water (if any) reaching the bottom. First 5 cm of bottom of all the

columns were filled with gravels. Air dried soils were then filled in suitable increments in the column up to 40 cm and after each fill, were compacted to desired bulk density level by applying appropriate blows of hammer (5 kg mass and diameter slightly less than the diameter of the columns). Bulk densities maintained for black, red alluvial and sandy soils were 1.4, 1.55, 1.5 and 1.6 Mg m⁻³, respectively.

4.1.3.2 Treatments of Laboratory study:

Main: soil types – sandy, alluvial, red and black.

Sub-treatments: Rate of Pusa hydrogel (a cross linked semi-synthetic polyacrylamide copolymer) application - 0.7% and 0.5% and 0% (by weight). In each column, required amount of gel was mixed with the upper 10 cm soil layer of PVC column. Soil moisture samples from four replications of each treatment were taken from 0-15 and 15-30 cm soil layers on each sampling date. Samples were collected on 4, 7, 14, and 22 days after watering (DAW) using a core auger.

4.1.3.3 Description of core auger and soil sampling for measuring of hydraulic properties:

Core auger consisted of cylinder (core) of 5 cm diameter and 6 cm height with 2 rings of same diameter but 2 cm height kept on either side. Rings with undisturbed soil were used in pressure plate apparatus for determination of water retention characteristics, whereas soil of the core in three replications was taken out in aluminum can, oven dried for determination of oven dry bulk density and gravimetric soil water content. Core with soil of the fourth replication was used for determining the saturated hydraulic conductivity by constant head permeameter method in laboratory. Soil moisture % calculated gravimetrically was converted to volumetric moisture % by multiplying it with bulk density. The soil moisture characteristics curve for each treatment was prepared by using pressure plate apparatus (Klute, 1986) for matric potential (Ψ) ranging from 0 to 1500 kPa.

Pan evaporation from an identical column filled with water instead of soil was measured daily to monitor the daily evaporation. The value of pan evaporation during the study period ranged between 0.65 to 1 mm day⁻¹.

4.1.3.4 Pore size distribution, moisture midpoint, pore median diameter and water release index:

The effective size of pores was calculated from the following equation (Marshall *et al.*, 1996):

$$r = -\rho_w g h = - \frac{(2\gamma \cos \alpha)}{\psi}$$

where r - mean equivalent cylindrical radius of pores (m) at a given matric potential ψ (Pa); γ - surface tension (72.75 mJ m⁻² at 20°C); α was contact angle between the water and pore wall, assumed to be zero); ρ_w - density of water (0.9982 Mg m⁻³ at 20°C); g - acceleration due to gravity (9.80 m s⁻²); and h - matric suction (m) applied just to drain the water. In the above study, the pores were grouped into three categories: transmission pores with diameter range between 30 -150 μ m corresponding to 0.2-1 m of matric suction (P_T), Storage pores with diameter range between 0.2-30 μ m corresponding to 1-150 m of water (P_S) and residual pores with diameter <0.2 μ m representing water retained at matric suction >150 m (P_R) as suggested by Greenland (1981).

The pore median diameter (d_m) *i.e.*, absolute matric potential at the mid-point (p) between the two limits of the soil moisture characteristics curve was computed using the formula given below

$$d_m(\mu m) = \frac{300}{\psi(kPa)}$$

where p was the absolute matric potential at the middle of the upper and lower limits of the soil water characteristic curve *i.e.*, at $\frac{(\theta_s + \theta_r)}{2}$ where θ_s = saturated soil water content and θ_r = residual soil-water content.

The water release index (I_m) [(%, v/v) / kPa] also referred as differential water capacity at the mid-point of the two limits of the soil-water characteristic curve, represented the amount of water release per unit change in soil matric potential around the mid-point.

Available water capacity (AWC) was calculated as the difference between soil water content at 30 kPa and 1500 kPa soil water suction. Whereas, readily available water capacity was calculated as the difference in soil water content at 10 kPa and 100 kPa soil water suction.

4.1.4 Results

4.1.4.1 Soil moisture distribution during drying:

Soil water distribution of 0-15 and 15-30 cm of red sandy loam, alluvial sandy loam, black clay and sandy soils were studied in PVC columns under variable gel application rates during a drying cycle after 5 cm of water application (Fig. 4.1.1).

Results revealed that for red sandy loam soil, soil water content (SWC) at surface layer (0-15 cm) measured on 4th, 7th, 14th and 22nd days after watering (DAW) in treatment with gel application @ 0.7% showed an increase by 12, 15, 6 and 6.13%, respectively over their values in no gel treatment.

In black clay soil, initially (4th DAW) the SWC of surface layer in 0.7% gel treated column was higher by 12% over its value of 33.37% in without gel treated column. During the later stages of drying *i.e.*, on 7th, 14th and 22nd DAW, the increase in SWC reduced to 6.74, 6.4 and 2% respectively.

In alluvial sandy loam soil initially (4th DAW) the SWC of surface layer in 0.7% gel treated column was higher by 19% over its value of 23.32% in no gel treated column. During further drying *i.e.*, on 7th, 14th and 22nd DAW the increase in SWC reduced to 17, 11 and 8%, respectively. In comparison to black and red soil types, in alluvial sandy loam soil, with passage of time, the differences in SWC between gel and without gel column narrowed down more gradually.

In sandy soil initially (4th DAW), the SWC of surface layer in gel treated column was higher by 14% over its value of 23.2% in no gel treated column. On 7th, 14th and 22nd DAW the increase in SWC reduced to 18, 13 and 4% respectively.

In sub-surface layer (15-30 cm) for all soil types except black, gel application @ 0.7% showed an appreciable decrease initially but the differences became marginal at the later stage. In black clay water content of sub-surface layer remained unaffected by gel application.

During initial stage of drying (4-7 DAW) (Fig. 4.1.2), among treatments without gel application, rate of soil water depletion from surface layer was maximum in black clay (3.45% per day) followed by sand (2% per day), red soil (1.75% per day) and lowest in alluvial soil (1 per day). During 7-22 days it reduced to <0.5% per day in almost all the soil types. However, the moisture depletion/release pattern of the soils

became different when gel was applied @ 0.7% in the upper 5 cm of those soils. Initially (4-7 DAW), in black and alluvial soils, rates of water release were higher (0.9-1.8 % per day) than in without gel treatments whereas they were lower (0.8%) in red and sandy soil. During 7-14 DAW, the rate of water release was around 1% per day in sandy and alluvial soils, 1.33 % per day in red and 0.5% in black soil. In other words, It can be stated that except black soil, in all other soils, rate of release of water per day during 7-14 DAW was higher by 0.5% per day or more when compared with treatments without gel. However during 14-22 DAW, only in sandy soil, rate of water release with gel application @ 0.7% was appreciably higher (1.39% per day) than without gel application treatment (0.33% per day).

4.1.4.2 Soil water characteristics curve:

At saturation (Fig. 4.1.3) among different soil types without gel application, SWC was maximum in black clay (53.97 %) followed by alluvial sandy loam (36.8%) and red soil (31.26 %), and lowest in sandy soil (30.45). Addition of gel at @0.7% increased the moisture at saturation by 21% in black clay, 40% in sandy soil, and 24% in alluvial and red sandy loam soils. At 10 kPa, soil water contents of sandy, black, red, and alluvial were higher by 40, 24, 37 and 24% over their value under no gel. At 100 kPa, the increase in soil water content with hydrogel application narrowed down in all soil types (9-15 %). At 1500 kPa, the increase in soil moisture retention with hydrogel application reduced further. In general it was observed that in all soil types except black, the addition of hydrogel @ 0.5% improved the moisture retention appreciably. Further additions of 0.2% of gel only increased the moisture content moderately. Similar results were also reported earlier (Abedi Koupai *et al.*, 2008; El-Hady *et al.*, 2009).

For better understanding of the water release pattern of different soil types under different rates of gel applications, soil water characteristic curve was divided into 4 categories, 0-10 kPa, 10-100 kPa, 100-300 kPa and 300-1500 kPa (Table 4.1.1). Water release per unit change in soil water suction in 0-10 kPa and 10-100 kPa range for red soil were 0.3 and 0.36 % kPa^{-1} in 0.7% gel and 0.53 and 0.17% kPa^{-1} in no gel treatment; for alluvial soil were 0.76 and 0.26% kPa^{-1} in 0.7% gel and 0.78 and 0.16% kPa^{-1} in no gel treatment; for sandy soil were 1.0 and 0.44% kPa^{-1} in 0.7% gel

treatments and 1.10 and 0.11% kPa^{-1} in no gel treatment; for black soil were 0.24 and 0.34% kPa^{-1} in 0.7% gel and 0.57 and 0.18% kPa^{-1} in no gel treatment. In 100-300 kPa range and beyond mostly the water release rate was $<0.05\% \text{ kPa}^{-1}$.

Midpoint soil moisture content (MPM) (Table 4.1.2) of the characteristic curve (indicative of moisture retention status) for each soil was computed by taking the average of soil water content at saturation and residual soil-water content *i.e.*, when soil reaches its wilting point soil moisture content. The computed MPM value was highest for black clay soil (41%), whereas for other soils it ranged between 17.5 to 21.8%. Addition of gel increased the magnitude of MPM in each soil. The increase was highest in sand (23%), followed by red (20%) and alluvial soil (17%) and least in black soil (12%).

Moisture release index (I_m) also showed appreciable decrease with gel application @ 0.7% in red and alluvial soils and relatively less decrease in sandy soil. Decrease of I_m with gel application was also an indicative of less release and hence more moisture retention per unit changes in suction around mid-point of characteristics curve.

Pore Median diameter (d_m) decreased with addition of gel in all the soil types. Reduction in pore diameter was indicative of increase in relatively small size retention pores. The reduction in pore median diameter with gel application was maximum in red (13.04 to 4.41 μm) and minimum in black soil (8.82 to 6.82 μm). Median diameter $< 6 \mu\text{m}$ was an indicative of decrease in drainage or aeration porosity due to gel addition (Sullivan and Ball, 1993).

4.1.4.3 Saturated hydraulic conductivity (K_s) and other hydraulic parameters:

In no gel treatments, measured K_s was highest in sand (89 cm day^{-1}) followed by red soil (63 cm day^{-1}) and alluvial soil (18 cm day^{-1}) but with gel addition (0.7%), it reduced to 40.75, 7.79 and 9.23 cm day^{-1} in sand, red and alluvial soils, respectively (Fig. 4.1.4). Lower K_s in gel treated red soil again showed the reduction in drainage porosity and increase in retention and residual pores with gel application in red soil.

Data of transmission porosity % (TP) (aeration porosity) (Table 4.1.3) showed that except in sandy soil, in all other soils its value was below the critical limit of 10% which indicated poor aeration status of these soils. Addition of gel did not change

transmission pores in sandy and alluvial soils but reduced them in red and black soils. Retention porosity (Ret P) on the other hand increased with gel application @ 0.7% in all soil types by 1.5-3 times. Not only retention pores, but residual pores (Res P) also increased with gel application in all soil types.

Available water capacity (AWC) of different soils without gel was in the order black (14.97) > alluvial (12.97) > sand (9.52) > red (6.97) but with gel application @ 0.7% the order changes to black (35.92) > red (31.1) > sand (29.59) > alluvial (23.14). Readily available water capacities (RAWC) (10-100 kPa) also increase on gel application in all soil types.

Significant correlations among various hydraulic parameters (Table 4.1.4) included positive correlation of K_s with TP and MPM, negative correlation of d_m with AWC and MPM, positive correlation of Ret P with AWC and RAWC.

4.1.5 Discussion:

Results of drying pattern of different soils showed higher soil water retention in surface soil layer in gel treatment over no gel. In all soil types, initially the water content of sub-surface soil of gel treated columns was less as compared to surface. This was due to more water retained by gel residing in upper surface layer which ultimately reduced the downward movement of water.

Water release pattern of sandy soil was different from other soil types. In other three soil types, maximum differences in SWC between gel and no gel treatment were observed on 4th day and later on the differences narrowed down, but in sandy soil the difference in SWC between gel and no gel treated column remained higher for long duration. Reason for such behavior was that in sandy soil due to less number of retention pores, the decrease in SWC between 4-7 days period was high (6.3%) in no gel treated column whereas in gel treated column because of increase in number of retention pores by gel application, the decrease in SWC with time was less (nearly 3.5%).

The water release per day in sandy soil with gel application @ 0.7%, was relatively uniform (1-1.4% per day) throughout the entire drying period. The reason for such behavior in sandy soil was that applied gel glued the inactive sand particles and as

the numbers of retention pores were increased considerably, hence water was released at moderate rates at lower suctions. Even at higher suctions, chemical bonding among gel, sand and water were not very strong to reduce its release to lower rates. In black clay soil, only during 4-7 DAW, the release was higher in gel treatment but later it became similar to that under without gel treatment. Reason for such release pattern was that in black soil there was abundance of active smectitic clay and addition of gel increased the chemical interaction (bonding) among gel, water and clay. Here also number of water retaining pores increased and therefore water release was higher at lower suction but water release rate reduced appreciably at higher suction due to increased bonding among clay, water and gel particles. In red and alluvial soils, water release per day ranged between 1- 2% during 4-14DAW and later reduced to 0.5 % per day or less which was similar to trend in no gel treatment. Here because of less reactive kaolinite and illite types of clay and their lesser amount as compared to black clay, the release rates remained moderate even at relatively higher suction.

Application of gel reduces the saturated hydraulic conductivity (K_s) significantly in all soil types due to addition of gel, soil particles were glued together, which resulted in increase in retention and residual pores and hence K_s was also reduced (Al-Darby *et al.*, 1992; El-Shafei *et al.*, 1992 and 1994; and Al-Darby, 1996).

Results of the soil moisture characteristics curve revealed that water release per unit suction change in 0-10 kPa range (corresponding to water released from drainage pores and unavailable to plants) under no gel was higher as compared to with gel. But water release per unit suction change in 10-100 kPa range (corresponding to water released from retention pores and is available to plants) under without gel was significantly lower when compared to gel treatments in all soil types. These results have thus indicated the superiority of gel in improving the water availability to plants. Looking at above trends it could further stated that in all soil types, soil water suction of 100 kPa could be considered as the critical limit of soil water potential as beyond it in all soils, water release per unit suction change became very less. The results were similar to reported earlier by Sullivan and Ball (1993).

In order to further confirm the suitability of gel in improving crop production in all soil types, next step of data analysis was to record critical soil water content (SWC

corresponding to 100 kPa) in all soil types and gel application rates. Its magnitude for red, alluvial, sand and black under 0.7% gel treatment was 36, 30, 20 and 41%, respectively and under no gel treatment was 10.86, 14.0, 9.48 and 32%, respectively.

After recording critical SWC data, soil water content on various days after watering was examined in each case to find out, during which drying stage this critical SWC was reached. It was observed that critical SWC for red, alluvial, sand and black under 0.7% gel treatment reached around 7-14, 7-14, 22 and 4-7 DAW, respectively. The result thus indicated that among all gel treated soil types, in sandy soil the critical soil water content reached after longest time interval.

4.1.6 Conclusion:

By noting the number of days in which the soil reaches critical SWC, following conclusions regarding the suitability of hydrogel for different soil types were made:

1. Hydrogel was found unsuitable for black soil because critical soil water content under gel treatment arrived early (4-7 days) and water transmission pores or aeration pores reduced drastically (much below the critical limit *i.e.*, 10% aeration porosity) in gel treated plot.
2. It was recommended highly suitable for raising agricultural crops on sandy soils mainly because of two reasons
 - i. In sandy soils, the soil water release per unit of suction change in 10-100 kPa range (plant available water range) was nearly 4 times higher than in without gel treatment.
 - ii. The time of arrival of critical SWC of hydrogel treated soil was near 22 days which matched with irrigation interval of most of the agricultural crops.
3. In alluvial and red sandy loam soils, it was found suitable for raising vegetable crops (where irrigation interval is between 10-15 days and critical SWC arrives around 14 DAW) as water available to plants increased by 1.5–2 times to that available under no gel condition.

From the above study following guidelines can be used for evaluating suitability of any gel or soil conditioners in improving the water availability for a given soil type.

A given concentration of gel or soil conditioner mixed with upper few cm (8-10) of soil should be watered and a tensiometer be installed near the middle of gel layer and soil

moisture tension should be recorded at regular interval till the tension reaches the maximum limit of 100 kPa. Soil moisture contents of gel and control plots should be measured at 10 and 100 kPa to compare RAWC. In case the magnitude of RAWC is higher in gel plots than in control, it will indicate that gel has improved the water available to the plant, but this result is not sufficient to draw conclusion about efficacy of gel. It is more important to note the time (days) when soil water tension of 100 kPa arrives in both the treatments. In case if it reaches after sufficiently longer time interval in gel plot which coincides with irrigation interval of the crops, it will be considered as a useful soil conditioner.

4.2 RESEARCH PAPER II



Evaluation of water retention and water release pattern of alluvial sandy loam soil in relation to soil amendment and hydrogel application

4.2.1 Abstract

A field study was conducted to monitor the water retention and release pattern of hydrogel treated sandy loam soil under different evaporative condition during soybean-wheat growth. Main treatment included two types of amendment FYM, tank soil @ 5 t ha⁻¹ and no amendments and sub-treatments with three rates of hydrogel application, 5, 2.5 and 0 kg ha⁻¹ applied at 5-7 cm depth along with seeds in rows using a manual seed drill. Soil water characteristics curves for different treatments were prepared by using undisturbed soil cores. Soil water content change at the surface layer was also regularly monitored

Results revealed that change in soil water content per unit change in suction became negligible after 100 kPa. Hence soil water content at 100 kPa suction was considered as critical soil water content (CSWC) beyond which water is not readily available to the plant. Soil water characteristic curve showed that at all suctions, water retained in gel treatments remained always higher.

In soybean, when pan evaporation ranged between 4-7 mm day⁻¹, SWC in FYM with gel treatment reached near its critical value in 14 days. Whereas, in other treatment this arrived early. In wheat, during early part of growth when pan evaporation ranged between 1-1.8 mm day⁻¹, CSWC arrived in 28 days in FYM with gel @ 5 kg ha⁻¹ treatment. However after 3rd and 4th irrigation in wheat, when pan evaporation rates ranged between 3-7 and 5-7 mm day⁻¹, even on 13th days after irrigation the values were appreciably below (6-7 %) their CSWC. Hence, it can be concluded that effectiveness of hydrogel gel in releasing moisture at higher rates has been restricted to shorter periods under high evaporative condition.

Key words: Critical soil water content, FYM, hydrogel,

4.2.2 Introduction:

Deterioration of natural resources, mainly soil and water, due to unscientific management practices has put sustainability of agricultural production systems at stake. Efficient management of soil water is important for agricultural production as the water resources are declining at faster rates. Soil amendments, both natural and synthetic, contribute significantly to provide a reservoir of soil water to plants on demand in the upper layers of the soil where the root systems normally develop. Since soil management systems influence soil physical conditions, it is important to determine the effect of natural and synthetic amendments on soil hydraulic properties (Verma and Sharma, 2008).

Long-term application of fertilizers and organic manure influence soil organic carbon (SOC content) (Benbi *et al.*, 1998; Shirani *et al.*, 2002), bulk density (D_b) (Benbi *et al.*, 1998; Miller *et al.*, 2002), structure (Schjønning *et al.*, 2002; Pagliai *et al.*, 2004), and hydraulic properties of soil (Miller *et al.*, 2002; Schjønning, 2002; Celik *et al.*, 2004). FYM increases the water infiltration and the aggregation of soils, it reduces the soil bulk density and may therefore, reduce runoff in the field (Ekwue and Stone, 1995; Gilley and Risse, 2000).

Hydrogel increases the amount of available moisture in the root zone, thus implying longer intervals between irrigations (Flannery and Busscher, 1982; Johnson, 1984a; Bowman and Evans, 1991). The amount of water retained by the sandy soil at each matric suction over the range of 100-15000 cm water significantly increased with increase of the gel-conditioner concentration (Al-Omran *et al.*, 1988; Al-Darby *et al.*, 1992; El-Shafei *et al.*, 1994).

Use of water absorbents in sandy soils from arid and semi-arid regions could serve as an important tool in increasing water-use efficiency and crop production. It has been postulated that adding polymers to sandy soils may improve water availability to plants, not only due to polymer swelling but also by decreasing the hydraulic conductivity of the sand, thus decreasing drainage of water below the root zone (Kazanskii and Dubrovskii, 1992; Al-Omran and Al-Harbi, 1998). Several studies

reported that there is a high exponential decrease in saturated hydraulic conductivity (K_s) of coarse texture soils with the increase of gel-conditioner concentrations (Al-Darby *et al.*, 1992; El-Shafei *et al.*, 1992 and 1994; and Al-Darby, 1996). On a sandy calcareous soil of Egypt, El-Hady and Sedera (2006) concluded that Incorporating 1 kg organic matter mixed with 1 g of acrylamide hydrogels reduced hydraulic conductivity by 43.5% as compared to control. More decrease in the values saturated hydraulic conductivity was obtained by raising the application rate of the mixture of both components.

The ratio between micro and macro-pores is of great importance in revealing the rate of water retention and water movement in the soil, incorporating the examined hydrogels into sandy soil beneficially modifies this ratio. While micro: macro porosity in the untreated soil was 0.27: 1, it increased by soil conditioning to be 0.55:1 and 0.76:1 due to the addition of 2 and 3 g hydrogel / plant pit respectively and to reach about 1:1 by addition of 4 g hydrogel to each plant pit of sandy soil indicating slow water movement and more water retention in the soil (El-Hady *et al.*, 2009; Asghari *et al.*, 2009).

In few studies contrasting results have been reported. Paluszek and Zembbrowski (2008) and Leciejewsk (2009) reported that in sandy loess soil treated with hydrogel increased macro pores and increases the hydraulic conductivity, but micro pores were unaffected. Moreover, most of the studies were conducted in laboratory, but their efficacy to improve hydraulic properties of soil in a field was not properly investigated.

Hence, the objective of this study was to determine the effects of soil amendments and hydrogel on soil hydraulic properties.

4.2.3 Material and Methods:

In order to achieve the objectives, field experiments on soybean-wheat cropping system were conducted during the *kharif* (July-November) (2009 and 2010) and *rabi*

season (November-April) of 2009-10 at the research farm of Indian Agricultural Research Institute, New Delhi.

4.2.3.1 Climate and soil:

The climate was semi-arid with average summer and winter temperatures ranging between 40°C - 42°C and 5°C - 8°C, respectively. The mean annual rainfall is 787 mm, of which 75 to 80 % occurs during the monsoon season (July to September). Air remains dry during most of the part of the year. Mean daily pan evaporation ranges from 7 to 1 mm during October to April. Mean daily values (during different weeks) of meteorological parameters recorded at the I.A.R.I. meteorological observatory adjoining to the experimental site during *kharif* and *rabi* seasons are presented in Fig. 3.1a , 3.1b and 3.1c (See Material and Methods, Chapter 3).

The soil is sandy loam (Typic Haplustept), noncalcareous, and neutral in reaction. Brief physico-chemical properties of soils of the experimental site along with amendments were presented in Table 4.2.1.

4.2.3.2 Treatments:

For soybean, the main treatment consisted of two soil amendments *i.e.*, tank soil (TS), farmyard manure (FYM), applied @ 5 t ha⁻¹ and no amendment (NA) and sub treatments consisted of three rates of Pusa hydrogel (across linked semi synthetic polyacrylamide copolymer) *i.e.*, 5, 2.5 and 0 kg ha⁻¹. Experiment was laid in split plot design. Treatments were replicated thrice. During wheat season, the main treatment amendments were not applied but their residual effect was seen. However the sub-treatments were similar to those of previous season.

4.2.3.3 Preparation of seed bed:

Both FYM and tank soil @ 5 t ha⁻¹ were incorporated in upper 15 cm of soil 7 days before the sowing of soybean with the help of hand spade. Desired rate of hydrogel was mixed with 1 kg of dry sand and applied in rows at 5-7 cm soil depth along with seeds by using a manually drawn seed drill so as to cover the entire plot.

4.2.3.4 Soil Sampling and Analysis:

Soil samples from each replicated plot were collected from the line where hydrogel was applied. For soil water content (SWC) determination, soil samples were collected from 0-15, 15-30, 30-45, 45-60, 60-75 and 75-90 cm soil layer using screw auger and SWC was determined gravimetrically. Calculated gravimetrically SWC% was converted to volumetric SWC% by multiplying it with bulk density. But as the hydrogel was mixed in surface layer, so variation of SWC of 0-15 cm layer has been presented here.

For determination of bulk density (BD) and saturated hydraulic conductivity (K_s) core auger was used. Core consisted of sectional cylinder (core) of 5 cm diameter and 6 cm height with 2 rings of same diameter but 2 cm height kept on either side. Rings with undisturbed soil were used in pressure plate apparatus for determination of water retention characteristics, whereas soil of the sectional cylinder/core was used to determination saturated hydraulic conductivity (K_s) by constant head method (Reynolds and Elrick, 2002). Another set of soil core was used for bulk density determination. The soil moisture characteristic curve for each treatment was obtained using the pressure plate apparatuses (Klute, 1986) for matric potential (Ψ) ranging from 0 to 1500 kPa.

4.2.3.5 Pore size distribution, moisture mid point, pore median diameter, available water capacity, readily available water capacity.

The effective size of pores was calculated from the following equation (Marshall *et al.*, 1996):

$$r = -\rho_w g h = -\frac{(2\gamma \cos\alpha)}{\psi}$$

where r is the mean equivalent cylindrical radius of pores (m) at a given matric potential ψ (Pa); γ the surface tension (72.75 mJ m^{-2} at 20°C); α - contact angle between the water and pore wall, assumed to be zero); ρ_w - density of water (0.9982 Mg m^{-3} at 20°C); g - acceleration caused by gravity (9.80 m s^{-2}); and h - matric suction or pressure head (m) applied just to drain the water. In our study, we grouped the pores into transmission pores ($[P_T]$ 30 to 150 μm diameter corresponding to 0.2-1m of water), storage pores ($[P_S]$ 0.2 to 30 μm diameter corresponding to 1-150 m of water) and residual pores ($[P_R]$ $<0.2 \mu\text{m}$ diameter representing water retained at >150 m matric suction) as suggested by Greenland (1981).

The pore median diameter (d_m) was computed using the formula given below

$$d_m (\mu\text{m}) = -300/p \text{ (kPa)}$$

where p is the absolute matric potential at moisture mid-point (MPM) which is the mid-point between the two limits of the soil moisture characteristic curve *i.e.*, at $[(\theta_s + \theta_r)/2]$, where θ_s = saturated soil water content and θ_r = residual soil-water content.

Available water capacity (AWC) was calculated as the difference between soil water content at 20 kPa and 1500 kPa soil water suction. Whereas, readily available water capacity (RAWC) was calculated as the difference in moisture content at 10 kPa and 100 kPa soil water suction.

4.2.3.6 Statistical analysis

Statistical analysis of field data was done by using the software MSTAT_C (1988).

4.2.4 Results:

4.2.4.1 Weather:

The weather data during the *kharif* (2009 and 2010) and *rabi* (2009-10) crop growth stage has been given in Fig. 3.1a, 3.1b and 3.1c (See Material and Methods, chapter 3). The meteorological data indicated mean weekly maximum temperature fluctuated between 31⁰C to 37.7⁰C during July to November (*kharif* season), 2009; between 26⁰C to 34.1⁰C during 2010 and between 15⁰C to 37.7⁰C during in *rabi* season, 2009-10. Total rainfall received during *kharif* was 489.6 mm during 2009 and 749.4 mm during 2010, while in *rabi* season total rainfall received was only 14 mm in 2009-10. Daily pan evaporation ranges from 1.2 to 7 mm during *kharif* (July to November) in 2009, and 1 to 6 mm in 2010, and 1.4 to 9 mm in *rabi* 2009-10.

4.2.4.2 Soil water characteristics curve:

At saturation among different soil amendments without gel application, SWC was maximum in FYM (49.09 %) followed by No amendment (46.82%) and lowest in Tank soil (44.92%) (Fig. 4.2.1).

Among amendment types maximum soil water content was found in FYM treatment at all soil water suction except at 10 kPa. Irrespective of amendment type, application of gel @ 2.5 and 5 kg ha⁻¹ increased SWC at all suctions. At 10 kPa soil water suction, FYM and tank soil treatments showed a decreased of 1% over the value

of 27.21 under no amendment. Application of gel @ 5 kg ha⁻¹ in all amendment types increased the water content by 9-10%. At 100 kPa, the increase in soil water content with hydrogel application narrowed down in all amendment types. At 1500 kPa increase in SWC with hydrogel application reduced further. Similar results were also reported earlier (Abedi Koupai *et al.*, 2008; El-Hady *et al.*, 2009).

In general, for better understanding of the water release pattern of different soil amendments under different rates of gel applications, soil water characteristic curve was divided into 0-10, 10-100 and 100-300 and 300-1500 kPa suction range (Table 4.2.2). Between 0-10 kPa, among the different amendment types, release per unit suction change was maximum in FYM (2.29% kPa⁻¹). Again with gel application @ 5kg ha⁻¹ release per unit change in suction decrease by 0.63 over 1.96 under no amendment; by 0.32 over 1.88 under tank soil and by 0.59 over 2.29 under FYM. Between 10-100 kPa, irrespective of amendment type application of gel @ 2.5 kg ha⁻¹ increased the release per unit suction change significantly but difference between two gel application rates were non-significant. Beyond 100 kPa the release per unit suction change was very less (< 0.03% kPa⁻¹).

Soil water retained at or beyond 1500 kPa was considered as the water stored in soil matrix which was unavailable to the plants. The amount of water locked at 1500 kPa by addition of gel ranged between 1-1.5% in all amendment types.

Since water release per unit suction change was very less beyond 100 kPa it was considered as critical soil water suction from water availability point of view. Therefore, soil water content retained at 100 kPa can be labeled as critical soil water content (CSWC). The value of CSWC for 0, 2.5 and 5 kg ha⁻¹ of gel application rates were 12.76, 13.98 and 15.67% in no amendment treatment; 12.96, 13.77 and 15.07% in tank soil; 13.98, 15.5 and 16.75% in FYM treatment. The above results thus show that with gel application CSWC increases by 2.5 to 3% over its value under without gel.

4.2.4.3 Soil moisture distribution during drying:

Moisture distribution of 0-15 cm of tank soil, no amendment and FYM were studied under variable gel application rates during a drying cycle after every irrigation or rain (Fig. 4.2.2a, 4.2.2b and 4.2.2c). Since the frequency of rain was high during initial and middle phase of soybean crop growth *i.e.*, mid of July to mid of September in

2009, so rainless period between two subsequent rainy days was less than 10 days. Only in late September after last irrigation drying pattern were studied on 83 DAS and 90 DAS *i.e.*, 7 and 14 days after irrigation (DAI) and pan evaporation values during these period varied between 4-6 mm day⁻¹.

Result revealed that in no amendment treatment on 7th DAI the SWC values under all rates of gel application were well above (2-3%) higher than their CSWC values. But on 14th DAI all were below (2-4%) their CSWC. Similarly in tank soil amendment, for all rates of gel application the SWC values were 3-4% below their CSWC. In FYM on 14th DAI for 2.5 and 5 kg ha⁻¹ of gel application treatment the values of SWC is just reached their critical value.

Hence it can be concluded that in *kharif* season where pan evaporation rates were high (4-7mm day⁻¹) only in FYM along with gel application @ 2.5 and 5 kg ha⁻¹, soil water content remained higher than their CSWC value up to 14 days.

In second year of *kharif* (2010) similar observation on SWC was recorded but the drying pattern was compared on 12th and 24th days after 14.18 cm rainfall occurred between 60 to 64 DAS (Fig. 4.2.2b). In second season as the pan evaporation rates were slightly higher than the previous year, in all treatments the soil water content reached below their CSWC values even on 12th day.

Hence it can be concluded that under high pan evaporation the effectiveness of gel is reduced to a shorter duration.

In *rabi* (2009-10) drying pattern was critically examined after every irrigation cycle (Fig 4.2.2c). Results revealed that on 16th days after irrigation (DAI) (1st irrigation cycle), the magnitude of SWC for all rates of gel application under no amendments were higher than their CSWC values. During this drying cycle the pan evaporation values ranged between 1.0-1.8 mm day⁻¹. But on 28th DAI the values under all gel application rates were crossed their CSWC. Again on 16th and 28th days after second irrigation similar trend were observed as the pan evaporation values were also similar (1.5 to 2 mm day⁻¹). However after 3rd and 4th irrigation where pan evaporation rate ranged between 3- 7 and 5-7 mm day⁻¹, even on 13th DAI the values were appreciably below (6-7 %) their CSWC. Similar trends were observed on tank soil treated plots.

In FYM under all gel application rates during drying after 1st and 2nd irrigation when the pan evaporation rates were also similar, it was observed that on 16th DAI, magnitude of SWC were 3-5% higher than their CSWC values. But on 28th DAI they reached near their critical values. On 13th days after 3rd and 4th irrigation the values reached appreciably (6-8%) below their critical values.

Hence it can be concluded that gel application was only effective when evaporation rates were lower ($< 2 \text{ mm day}^{-1}$). The gel along with FYM prolonged the moisture availability for relatively longer period, provided that pan evaporation rates were lower.

4.2.4.4 Pore size distribution, moisture mid point, median pore diameter, available water capacity and readily available water capacity.

Pore size distribution under different treatments was studied at the harvest of 1st season of soybean crop. In all amendment types, by gel application, transmission pores (TP) (drainage pores which contain water unavailable to plants) reduced significantly (5-6%), whereas retention pores (Ret P) (containing plant available water) increased by 7-9% (Table 4.2.3). Residual pores (Res P) which contain water locked in soil matrix were also increased by 1%. Among different amendment types, TP were 3.3% more, Ret P were 2% less and were Res P 1 % more in FYM as compared to 19.61, 21.47 and 5.74 % respectively, under no amendment.

In all amendment types, with gel application @5 kg ha⁻¹ the AWC increased by 3- 4.25% whereas RAWC increased by 6-8%.

Mid point soil moisture content (MPM) of the characteristic curve (indicative of moisture retention status) for each soil was computed by taking the average of soil water content at saturation and wilting point soil moisture content. The computed MPM value was highest for FYM (27.92%). Addition of gel increased the magnitude of MPM in each amendment.

Pore median diameter (d_m) decreased with addition of gel in all amendment types. Reduction in pore diameter was indicative of increase in relatively small size retention pores. The reduction in pore median diameter with gel application was maximum in FYM (27.27 to 20.69 μm) and minimum both tank soil and no amendment

(25 to 20 μm). Median diameter was an indicative of decrease in drainage or aeration porosity due to gel addition (Sullivan and Ball, 1993).

4.2.4.5 Saturated hydraulic conductivity

Results of hydraulic conductivity (K_s) (Table 4.2.4) measured in laboratory showed that on an average application of FYM increased K_s by 46% where as application of tank soil decreased K_s by 23% over a value of 13.67 cm day^{-1} under no amendment. Application of hydrogel @ 2.5 and 5 kg ha^{-1} reduced K_s by 45 and 60% over a value of 12.32 cm day^{-1} under treatment without gel application. In all amendments on increasing the gel application rate from 0 to 2.5 and from 2.5 to 5 kg ha^{-1} , magnitude of K_s was reduced significantly.

In comparison to *kharif*, K_s of all treatment showed a slight decrease. It was mainly due to the fact that in *rabi* soil was not thoroughly ploughed (only hand ploughing with spade in upper surface was done). However the trends showing the effects of gel and amendment application were similar to those obtained in previous season.

4.2.5 Discussion:

Addition of FYM significantly increased transmission pores as compared to no amendment. Even though the AWSC under different amendments was same but due to lesser rate of release per unit suction change under FYM, the soil water content remained higher as compared to other treatments. It was mainly because of fact that easily decomposable fraction of FYM *i.e.*, polysaccharides and polyuronides form linkages with soil particles and water molecules and therefore restricts their release.

However for all amendment types, gel application reduced TP, increased Ret P, AWC and RAWC significantly, mainly because of the increased adhesion between inter and intra aggregate soil particles and gel. Reduction in TP and increase in Ret P due to gel application was also reflected in significant reduction in saturated hydraulic conductivity.

It was evident from the soil water characteristic curve that in all amendment types, with gel application, release per unit suction change in surface soil became less in 0-10 kPa range, more in 10-100 kPa (plant available water range) and very less beyond

100kPa. Hence 100 kPa was termed as critical soil water potential and corresponding soil water content was termed as critical soil water content (CSWC).

Drying pattern of soil under different treatments revealed that CSWC increased with gel application in all amendment types. Besides, CSWC was also dependent on atmospheric evaporative demand. Under low evaporative demand, by gel application CSWC arrived after a long time interval and therefore higher water release rates were obtained for longer duration. On the other hand, under high evaporative demand condition the beneficial effect of gel lasted for relatively shorter periods.

4.2.6 Conclusion:

By addition of gel in soil transmission porosity reduced which was reflected in reduction in K_s . On the other hand, retention porosity increased which improved both AWC and RAWC.

It can be stated that under low pan evaporative demands, during the drying cycle following irrigation in FYM along with gel application, soil water content remains higher than its critical value for a longer period (>16 days). Whereas, under high pan evaporative condition, soil water content in gel treated plots reached its critical value earlier and therefore, effectiveness of gel in releasing water at higher rates is restricted only for shorter periods.

4.3 RESEARCH PAPER III



Modifying soil physical environment through amendment and hydrogel application.

4.3.1 Abstract:

Soil amendments and conditioners such as FYM, tank soil and hydrogels have the potential to improve the soil structure and water retention capacity of soil which in turn modifies other soil properties such as soil mechanical impedance, water stability of aggregates, soil hydraulic properties and soil temperature. Use of hydrogels for raising agriculture crops could be an economically viable option only if they are applied in smaller quantities at shallow depths in rows just below the seeds. In order to test the efficiency of hydrogel applied in such small quantities in improving the hydro-physical environment of alluvial sandy loam soil, a field study was conducted at the Indian Agricultural Research Institute, New Delhi. The main treatments include FYM and tank soil applied @ 5 t ha⁻¹ and no amendment and sub-treatments included three rates of hydrogel *i.e.*, 5, 2.5 and 0 kg ha⁻¹. Hydrogel was applied at 5-7 cm depth just below the seed in rows using a manual seed drill. Soil structural condition was monitored by evaluating structural indices, mechanical strength by measuring soil penetration resistance, hydraulic behaviour through saturated hydraulic conductivity and soil thermal environment by measuring the soil temperature.

Results revealed that FYM along with gel application @ 5 kg ha⁻¹ showed increase in mean weight diameter by 2 times, water stable structural units by 1.5 times and structural coefficient by 1.8 times over its value under treatment without amendment and gel. Both during soybean and wheat growth the penetration resistance was significantly reduced in FYM as compared to no amendment and also under gel application @ 5 kg ha⁻¹ as compared to no gel application mainly because of higher soil water content in FYM treated soil with hydrogel application. Saturated hydraulic conductivity (K_s) was reduced drastically by gel application due to reduction in transmission pores.

In general, hydrogel application reduced soil temperature because of more moisture retention by gel. All throughout the day the decrease in temperature with depth

was maximum in treatment without hydrogel and least in treatment with hydrogel application @ 5 kg ha⁻¹. It was mainly because of higher SWC of soils in gel treated plots which improved soil volumetric heat capacity and thus resisted its temperature increase. Moreover higher soil thermal conductivity due to high soil water content of gel treated plots quickly transported the heat from the surface to the deeper soil layer.

Hence it can be concluded that hydrogel along with FYM improved soil structure, lowered soil mechanical impedance, retained more soil moisture, reduced saturated hydraulic conductivity and kept the soil environment cooler as compared to control in the surface layer and thus created a favourable soil physical environment for better crop growth.

Key words: FYM, hydrogel, mean weight diameter, soil temperature

4.3.2 Introduction:

Manure application improved aggregate stability, which might have been associated with increased SOC concentration and soil biological activities (Haynes and Naidu, 1998; Chadravansi *et al.*, 1999; Aoyama *et al.*, 2000; Tripathi and Singh, 2004). The importance of organic matter in improving soil physical properties and processes has widely been documented (Reeves, 1997; Zebarth *et al.*, 1999; Franzluebbers, 2002; Celik *et al.*, 2004; Madari *et al.*, 2005). Long-term application of fertilizers and organic manure influence SOC content (Benbi *et al.*, 1998; Shirani *et al.*, 2002), bulk density (D_b) (Benbi *et al.*, 1998; Miller *et al.*, 2002), structure (Schjønning *et al.*, 2002; Pagliai *et al.*, 2004), and hydraulic properties of soil (Miller *et al.*, 2002; Schjønning, 2002; Celik *et al.*, 2004). FYM increases the water infiltration and the aggregation of soils, it reduces the soil bulk density and it may therefore reduce runoff in the field (Ekwue and Stone, 1995; Gilley and Risse, 2000). Other studies reported that physical condition of coarse textured soil was improved water holding capacity, aggregate stability, respiratory activity increased, simultaneously decrease in macro pore space, saturated hydraulic conductivity, achieved when different soil conditioners applied in a combination (El-Hady and Sedera, 2006; Asghari *et al.*, 2009).

Hydrogels potentially influence infiltration rates, density, soil structure, compaction, soil texture, aggregate stability and crust hardness (Helalia and Letey, 1988; Helalia and Letey, 1989), and evaporation rates (Teyel and El-Hady, 1981).

Application of anionic PAM with a molecular weight of 107 D_a on a sandy loam soil significantly ($P \leq 0.05$) increased mean weight diameter (MWD), water stable aggregates ($> 0.25\text{mm}$ diameter), and consequently prevented surface sealing (Levy and Miller, 1999; Paluszek and Zembrowski, 2008; Asghari *et al.*, 2009). It has been reported that addition of polymers to sandy soils improved water availability to plants, not only due to polymer swelling but also by decreasing the hydraulic conductivity of the sand; thus decreasing drainage of water below the root zone and also by increasing retention pores (Kazanskii and Dubrovskii, 1992; El-Shafei *et al.*, 1992; Al-Darby, 1996; Al-Omran and Al-Harbi, 1998; El-Hady and Sedera, 2006). It is expected that applying organic materials mixed with the proper hydrogel to the soil maybe more effective and economic than using each of them alone (Abd El-Hameed *et al.*, 1995; El-Hady *et al.*, 2000a; El-Hady *et al.*, 2002; El-Hady *et al.*, 2000b).

Soil compaction is a major cause of soil degradation in most agricultural soils (Van Lynden, 2000). In a compacted soil, the particles are pressed together, thus reducing pore spaces which contain air and water necessary for good plant growth (Aina *et al.*, 1985). Application of polyacrylamide (PAM), pumice, and straw as soil conditioners on the 5 cm layer of a sandy loam soil significantly ($P \leq 0.01$) decreased surface sealing by decreasing bulk density and increasing micro porosity (Sadegian *et al.*, 2006). Conditioning effects of organic materials, in terms of increasing water holding capacity, modifying bulk densities and pore size distribution, are more pronounced for coarse-textured soils than for medium and fine texture soils (Nelson and Kladienko, 1979; Metzger and Yaron, 1987; Bauer and Black, 1992). Based on two year study on a sandy soil of Egypt El-Hady *et al.* (2009) revealed that applying acrylamide hydrogels decreased the bulk density of the soil as well as the macro-porosity (drainable pores having the diameter of $> 28.8 \mu$) relative to those of untreated soil but showed opposite trend to micro-porosity.

Soil temperature is agriculturally more significant than aerial temperature (Chaudhary and Prihar, 1974). Soil temperature is one of the most important factors that affect the soil water flux, soil heat storage, soil heat flux, seed emergence, nutrient uptake and plant growth. The functional activity of plant roots can be affected at both low and high soil temperatures (Van Duin, 1963; Pollock, 1990). The soil temperature

was lower for all the layers under residue mulch (Kalra *et al.*, 1984; Tomar and Verma, 1985).

Despite the literature just cited, the effects of natural and synthetic soil conditioner on soil properties (soil temperature, aggregate stability) have not been thoroughly investigated. Moreover most of these studies mainly confined to the pot study, in field their effects not properly investigated.

The objectives of the present study were to investigate the effects of natural soil amendments (FYM and Tank soil) and Hydrogel (a cross linked semi-synthetic polyacrylamide copolymer) on soil physical environment namely aggregate stability, soil penetration resistance, saturated hydraulic conductivity (K_s) and soil temperature of a sandy loam soil during soybean-wheat growth.

4.3.3 Material and Methods:

In order to achieve the objectives, field experiments on soybean-wheat cropping system were conducted during the *kharif* and *rabi* season of 2009-10 at the research farm of Indian Agricultural research Institute, New Delhi.

4.3.3.1 Weather and soil:

The weather data during the *kharif* (2009 and 2010) and *rabi* (2009-10) crop growth stage has been given in Fig. 3.1a, 3.1b and 3.1c (See Material and Methods, Chapter 3). The meteorological data indicated mean weekly maximum temperature fluctuated from 31⁰C to 37.7⁰C during July to November (*kharif* season), 2009; from 26⁰C to 34.1⁰C during 2010 and from 15⁰C to 37.7⁰C during in *rabi* season, 2009-10. Total rainfall received during *kharif* (2009) was 489.6 mm and 749.4 mm during 2010 while in *rabi* season total rainfall received was only 14 mm in 2009-10. Daily pan evaporation ranged from 1.2 to 7 mm during *kharif* (July to November) in 2009 and 1 to 6 mm in 2010 and 1.4 to 9 mm in *rabi* 2009-10.

The soil was sandy loam (Typic Haplustept), noncalcareous, and neutral in reaction. Brief physico-chemical properties of soils of the experimental site and amendments are presented in Table 4.2.1. (See research paper II).

4.3.3.2 Treatments:

Main treatments consisted of three soil amendments namely tank soil @ 5 t ha⁻¹ (TS), farmyard manure @ 5 t ha⁻¹ (FYM) and no amendment (NA) and three rates of application of Pusa hydrogel (a cross linked semi-synthetic polyacrylamide copolymer) @ 5, 2.5 and 0 kg ha⁻¹ as sub-treatments. Experiment was laid in split plot design and each treatment was replicated three times.

4.3.3.3 Preparation of seed bed:

Desired rate of hydrogel was mixed with 1 kg of dry sand and applied in rows at 5-7 cm soil depth along with seeds by using a manually drawn seed drill so as to cover the entire plot.

4.3.3.4 Soil Aggregate Analysis:

Air dried soil was passed through 8 mm sieve and then through 4 mm sieve. The 50 gram of soil aggregates retained on 4 mm sieve was used as sample for wet sieving analysis. Wet sieving was done mechanically in Yoder's apparatus. The nest of sieves used had mesh size of 4, 2, 1, 0.5, 0.25, and 0.125 mm (Kemper and Rosenau, 1986). Wet sieving was continued for 15 min with 30 oscillations per minute. The aggregates retained on each sieve were transferred to a set of pre-weighed beakers, oven-dried at 60°C for 24 hours and weighed. The mean weight diameter (MWD) was calculated as an index of aggregation (Van Bavel, 1949) along with other indices as follows:

4.3.3.4.1 Water stable structural unit (WSSU):

The line between macro and micro-aggregates is commonly drawn at 0.25 mm (Edwards and Bremner, 1967; Oades and Waters, 1991). In the present study, the macro aggregates were determined by adding the aggregates retained over 4, 2, 1, 0.5 and 0.25 mm.

4.3.3.4.2 Mean weight diameter (MWD) of aggregates (Kemper and Roseneau, 1986):

$$\text{MWD} = \sum x_i w_i$$

where, w_i is the proportion of aggregates retained over the sieves in relation to the whole, x_i the mean diameter of the class (mm).

4.3.3.4.3 Structure coefficient (Cr): The ratio of the percentage of the total amount of fractions greater than 0.25 mm in diameter to the percentage of fraction having diameter less than 0.25 mm (El-Shafei and Ragab, 1976).

4.3.3.5 Soil Sampling and Analysis:

Soil samples from each plot were collected from the row where hydrogel was applied. For soil water content (SWC) determination, soil samples were collected from 0-15, 15-30, 30-45, 45-60, 60-75 and 75-90 cm soil layer using screw auger and SWC was determined gravimetrically. Calculated gravimetrically SWC% was converted to volumetric SWC% by multiplying it with bulk density. But as the hydrogel was mixed in surface layer, so variation of SWC of 0-15 cm layer has been presented here.

For determination of bulk density (BD) and saturated hydraulic conductivity (K_s) core auger was used. Core auger consisted of cylinder (core) of 5 cm diameter and 6 cm height with 2 rings of same diameter but 2 cm height kept on either side. Soil of the sectional cylinder/core was used to determination saturated hydraulic conductivity (K_s) by constant head method (Reynolds and Elrick, 2002). Another set of soil core was used for bulk density determination.

4.3.3.6 Penetration Resistance:

Soil penetration resistance (PR) was measured by using Rimik cone penetrometer (model no. CP20) on the lines where hydrogel was applied.

4.3.3.7 Soil temperature:

The soil temperature (ST) of 0-5, 5-10 and 10-15 cm soil layers was recorded on different days after sowing (DAS) (for variable soil water and air temperature conditions) using a digital thermometer. It was recorded at 1430 hrs during *khariif* season and at hourly interval during day time in *rabi* season.

4.3.3.8 Statistical analysis

The design of the experiment was split plot design. Statistical analysis of field data was done by using the software MSTAT_C (1988).

4.3.4 Results:

4.3.4.1 Aggregate stability:

Mean weight diameter of aggregates (MWD) (Table 4.3.1a) increased by 35 and 73% on application of gel @ 2.5 and 5 kg ha⁻¹, respectively over 0.45 mm under treatment without any amendment and gel application (control). Application of FYM alone increased MWD by 71% over control. However tank soil application alone did not improve MWD. Similarly, application of FYM along with gel application @ 2.5 and 5 kg ha⁻¹ increased it by 91 and 110%. Whereas application of TS along with gel application @ 2.5 and 5 kg ha⁻¹ increased it by 44 and 53%.

Hence, it can be stated that irrespective of amendment type, increase in gel application rate from 0 to 2.5 kg ha⁻¹ and from 2.5 to 5 kg ha⁻¹ increased MWD significantly. Among, different amendment types, addition of FYM significantly improved MWD.

Measured values of MWD at harvest of wheat also showed significant improvement in MWD with gel application (Table 4.3.1b). A residual effect of FYM application on change in MWD was also observed (magnitude of MWD increased from 0.54 mm under control to 0.94 mm under FYM).

Water stable structural units (WSSU) *i.e.*, percentage of aggregates >0.25 mm in size were found to increase from 16.8% under control to 20.8% under TS and 24.4% under FYM application. For all amendments, application of gel increased WSSU by 5-10%. However, under FYM and control treatments, for both gel application rates the differences were not appreciable.

In order to compare aggregation capacity of different treatments, structure coefficient (Cr) (the ratio of the percentage of the total amount of fractions greater than 0.25 mm in diameter to the percentage of fraction having the diameter less than 0.25 mm as suggested by El-Shafei and Ragab (1976) was calculated. Values of computed Cr showed a marked increase on application of either FYM or hydrogel or both

together. Application of TS and FYM raised this index to 1.08 and 1.22 times that of the control.

In wheat season, similar trend was observed *i.e.*, with application gel WSSU was increased in no amendment and FYM treated plots but in tank soil treated plots negative trend was noticed.

Values of computed Cr also showed trends similar to those obtained earlier where Cr was found to increase with gel application and also with addition of amendments.

In comparison to *kharif* season, during *rabi* season, the magnitude of all three aggregation indices showed a marked increase, indicating persistent residual effects of hydrogel, amendments and crop residue incorporation of the previous crop.

4.3.4.2 Soil moisture:

Moisture distribution of 0-15 cm of tank soil, no amendment and FYM were studied under variable gel application rates during a drying cycle after every irrigation or rain (Fig 4.3.1a, 4.3.1b and 4.3.1c).

Results revealed that among the amendment types FYM treated soil contained more moisture than the other amendment types. Application of gel @ 2.5 and 5 kg ha⁻¹ increased the moisture content of soil irrespective of amendment types, although increase in gel application rate from 2.5 to 5 kg ha⁻¹, moisture content increased slightly.

4.3.4.3 Saturated hydraulic conductivity

Results of hydraulic conductivity (K_s) (see Table 4.2.4) measured in laboratory showed that on an average application of FYM increased K_s by 46% whereas application of tank soil decreased K_s by 23% over a value of 13.67 cm day⁻¹ under no amendment. Application of hydrogel @ 2.5 and 5 kg ha⁻¹ reduced K_s by 45 and 60 % over a value of 12.32 cm day⁻¹ under treatment without gel application. In all amendments on increasing the gel application rate from 0 to 2.5 and from 2.5 to 5 kg ha⁻¹, magnitude of K_s was reduced significantly.

In comparison to *kharif* K_s of all the treatment showed a slight decrease. It was mainly due to the fact that in *rabi* soil was not thoroughly ploughed (only hand ploughing with spade in upper surface was done). However, the trends showing the

effects of gel and amendment application were similar to those obtained in previous season.

Saturated hydraulic conductivity was also measured in field by Guelph permeameter (K_{fs}) at 5 and 10 cm soil depths and their average value was presented (Fig. 4.3.2). In general K_{fs} was 3-8 times of K_s . The reason of higher value of K_{fs} was mainly because in addition to vertical movement of water, in field condition there was horizontal movement of water.

4.3.4.4 Bulk density and penetration resistance:

Bulk density (BD) (Table 4.3.2) differences among different amendment and gel treatments were not statistically significant at harvest of soybean and wheat, although BD of FYM with gel application @ 5 kg ha⁻¹ was slightly lower than rest of the treatments.

Soil penetration resistance was measured by Rimik cone penetrometer initially 45 DAS in soybean (Fig.4.3.3a). In all the treatments, results showed lower penetration resistance (PR) (less than 1000 kPa) even though SWC was below 10% (g/g). It was mainly because soil was loose as the field was tilled thoroughly by making 3 passes of disk harrow followed by to passes of tiller. In FYM treatment as compared to control, SWC was lower by 0.8(%, g/g) and hence the magnitude of PR was also lower. Higher soil water content in FYM treatment was mainly because of higher number of retention pores.

On 90 DAS range of soil water content under different treatments was similar to that 45 DAS, but PR values were mostly on the higher side in all treatments. It may be due to high rainfall during 50 to 65 DAS followed by continuous drying 65 to 90 DAS which broke down aggregates and caused surface sealing. Regarding the effect of amendment and gel application on PR, trend was similar to that observed on 45 DAS.

In wheat on 49th DAS, variation of SWC among the different treatments was between 6.2 to 10.5 (%, g/g) and the corresponding variation in PR was 650 to 2000 kPa (Fig. 4.3.3b). Magnitude of PR was similar in TS and No amendment treatments but it was significantly lower in FYM treatment. Addition of hydrogel in all amendment types reduced the PR appreciably.

On 90th DAS, soil wetness ranged from 16.68 to 22.8 (% g/g) and PR varied between 150 to 1000 kPa. In comparison to 49th DAS, in all treatments the magnitude of PR was comparatively lower because of wetter soil condition. Trend regarding the effect of amendment and gel application on PR was similar to that observed at the earlier stage (49th DAS).

On 99th DAS range of variation of SWC was between 6.97 to 11.05 (% g/g) and PR ranged from 1027 to 2434 kPa. From the above data it is apparent that even though the soil water contents of various treatments were similar both on 49th DAS and 99th DAS but the PR values were slightly higher on 99th DAS. It clearly reflected that effect of increased compaction leading to higher mechanical impedance at the later stages of growth.

Correlation between PR and SWC data collected during *rabi* season showed R^2 value of 0.92, which clearly indicated the highly significant effect of SWC on PR (Fig. 4.3.4).

4.3.4.5 Soil temperature:

Soil temperature at 2, 5 and 10 cm depth was measured between 1430 to 1500 hrs. at variable air temperature / evaporative conditions on 57 days after sowing (DAS) when maximum air temperature was 31⁰C and corresponding relative humidity and pan evaporation were 66% and 3.8 mm, respectively (Fig. 4.3.5a). Near surface (at 2 cm soil depth) soil temperature (ST) in TS and no amendment treatments were similar (31.3⁰C), whereas in FYM it was lowered by 1.1⁰C. In all amendments types, addition of hydrogel reduced the soil temperature by 1⁰C.

In comparison to surface, at 5 cm soil depth reduction in ST occurred in all treatments, but it was more visible in TS and no amendment treatments (2.8⁰C) where gel was not applied. At 10 cm soil depth magnitude of reduction relative to that of 5 cm depth was less (ranged between 1 to 2.8⁰C). In all amendment types, SWC increased with gel application by 2 to 2.5%.

Similar type of results were found on 76 DAS when maximum air temperature was 36.2⁰C and corresponding relative humidity and pan evaporation was 40% and 7.1 mm, respectively. But on 57 DAS, differences in soil temperature between various treatments were less pronounced than on 76 DAS because of low air temperature and

low evaporative condition. During second year of *kharif* season (2010), ST observation on different DAS (35 and 87) corresponding to high and low soil water conditions also showed trend similar to previous year (Fig. 4.3.5b).

The above results thus clearly indicated that as the soil water content in FYM was higher than in no amendment treatment, hence ST measured both near surface and at 5cm in FYM were relatively lower. In general, hydrogel application reduced ST under all amendment types because of more moisture retention by gel. However, effect of gel application in lowering ST was more visible in no amendment type than in FYM treatment mainly because of fact that increase in SWC by gel application in FYM was relatively less.

Increase in soil water content due to gel application increased the volumetric heat capacity of soil and hence during noon (when soil is heated) for given amounts of heat supply the increase in soil temperature was less in gel treated plots.. The results also clearly indicated that addition of hydrogel increased ST at 10 cm soil depth, which was due to increase in soil thermal conductivity, which increased with soil water content. The effects were more noticeable in TS and no amendment treatment as compared to FYM, because with gel application, larger variation of SWC was observed in the former treatments.

Soil temperature under different hydrogel application treatments was monitored at hourly interval during day time for variable soil water and air temperature conditions. Initially soil temperature was monitored on 25th DAS (5days after irrigation) under wetter soil condition (Fig. 4.3.5c1, 4.3.5c2 and 4.3.5c2). In all treatments, peak occurred at 1400 hrs. at surface and at 1700 hrs. at 10 cm. On 49th DAS under drier soil condition (29 days after irrigation) also, all throughout the day ST at all depth were higher in treatment without gel. Similar trend was observed in 90th DAS, but due to high air temperature soil temperature was higher in all the treatments. In general it was observed that under wetter soil condition (4 to 5 days after irrigation), peak soil temperature was lower than maximum air temperature, whereas under drier soil condition (25 to 30 days after irrigation) it was always higher.

4.3.5 Discussion:

Effect of amendment and gel on soil physical environment was assessed by monitoring aggregate stability, mechanical impedance offered by soil, saturated hydraulic conductivity, soil water content and soil temperature during crop growth.

In order to ascertain aggregate stability by addition of amendments and gel, structural indices, namely MWD, WSSU and Cr were computed which showed marked improvement in stability of both macro and micro-aggregates by incorporation of gel application alone or along with FYM.

In wheat season it was observed that application of gel, WSSU was increased in no amendment and FYM treated plots but in tank soil treated plots negative trend was noticed. This ambiguity could be due to non-inclusion of different diameter classes in calculation of WSSU where only weights of size fractions > 0.25 mm were considered. In contrast to WSSU, in MWD both weights and diameter of all classes were used in computation.

Applications of gel along with FYM showed significantly lower PR mainly because of significantly higher soil water retention which acted as lubricant and reduced frictional forces and thus reduced mechanical impedance to the penetrating probe. On comparing the initial PR values of both season (45th DAS in *kharif* and 49th DAS in *rabi*) it was observed that PR values were relatively on higher side in *rabi*. As the SWC range was similar during those times in both seasons, higher PR in *rabi* was due to higher compaction status (bulk density) from the very beginning of *rabi* season, which was mainly due to the fact that soil was not properly tilled before sowing of *rabi* crop. Only upper few centimeter soils were disturbed by ploughing it manually using a spade. Reason for not doing mechanical tilling was to maintain the same layout without disturbing the plots which existed in *kharif* season, so that the residual effects of amendments applied in *kharif* on succeeding *rabi* crop could be observed.

The increase in K_s due to FYM incorporation was because of increase in porosity. Whereas on addition of gel, particles were glued together resulting in decrease in transmission pores and hence K_s were also reduced. Results of saturated hydraulic conductivity measured in field (K_{fs}) by Guelph permeameter showed that it was on higher side than measured in laboratory. The reason of higher value of K_{fs} was mainly

because in addition to vertical movement of water, in field condition there was horizontal movement of water.

It was also observed that mostly throughout the day, rate of temperature change ($^{\circ}\text{C hr}^{-1}$) for all soil depths (2, 5 and 10 cm) was more in treatment without hydrogel than in treatment with hydrogel application @ 5 kg ha^{-1} . This was again because of lower thermal capacity of soil with lesser SWC in no gel treatment which caused more rapid temperature increase for same amount of heat supply. In addition to this, the temperature gradient ($^{\circ}\text{C cm}^{-1}$) was also higher in treatment without hydrogel than in treatment with hydrogel application @ 5 kg ha^{-1} . This was also because of lower thermal conductivity of soil (because of low SWC) in no gel treatment, which did not allow fast heat transport to deeper layers.

4.3.6 Conclusions:

Hydrogel along with FYM improved soil structure, lowered soil mechanical impedance, retained more soil moisture, reduced saturated hydraulic conductivity and kept the soil environment cooler as compared to control and thus created favourable soil physical environment for optimum crop growth.

4.4 RESEARCH PAPER IV



Effects of amendments and hydrogel application on growth and yield performance of soybean-wheat cropping system.

4.4.1 Abstract

Use of hydrogels along with amendments such as FYM in commercial agriculture is increasing mainly for improving structural stability and soil water retention for enhancing growth and water use efficiency of agricultural crops, vegetables and horticultural crops. In order to test the efficacy of Pusa hydrogel, a field study was conducted during soybean-wheat growth. Main treatment included three amendment types namely FYM, tank soil applied @ 5 t ha⁻¹ and no amendments and sub-treatments included three rates of hydrogel *i.e.*, 5, 2.5 and 0 kg ha⁻¹ applied at 5-7 cm depth along with seed in rows using a manual seed drill. Crop growth parameter studied included leaf area index (LAI), biomass, root length density (RLD), root surface density (RSD) and grain yield. Besides water use and water use efficiency (WUE) of soybean and wheat were also computed.

Results revealed that conditioners significantly increased LAI, the dry weights, root length density (RLD), root surface density (RSD), grain yield and water use efficiency by the plants. The beneficial effects of mixtures of FYM and hydrogel exceeded that of each conditioner when solely added. Application of hydrogel @ 2.5 kg ha⁻¹ significantly increased the dry biomass, root growth, grain yield and water use efficiency over no hydrogel, while further increased in hydrogel application @ 5 kg ha⁻¹ growth parameters and water use efficiency increased marginally.

Key words: hydrogel, soybean, LAI, biomass, root length density

4.4.2 Introduction:

Although soybean-wheat is one of the most dominant cropping systems in Vertisols of central India but in the trans Indo-Gangetic Plains (Inceptisols), where water table is declining, soybean-wheat system is emerging as an alternate to rice-wheat cropping system.

Maintenance of soil organic C (SOC) is considered essential for long-term sustainable agriculture because declining SOC levels in soil generally lead to decrease in productivity. Soil organic carbon (SOC) affects productivity through its effects on soil structure, plant available water capacity, soil buffering capacity and as a source of plant nutrients. Yields of soybean-wheat cropping system decreased with time under the unfertilized and the inorganic fertilizer treatments, whereas yields was significantly increased in the plots under N + FYM and NPK + FYM treatments (Behera, 2005; Kundu *et al.*, 2007).

Hydrogels, which were developed to increase water holding capacity of amended media, have been used to aid plant establishment and growth in dry soils. Plants grown in substrates amended with hydrophilic polymers were slower to wilt than those in unamended medium (Still, 1976; Conover and Poole, 1979; Gehring and Lewis, 1980; Baasiri *et al.*, 1986; Woodhouse and Johnson, 1991; El-Hady *et al.*, 2009). Mixing super absorbent materials (hydrogel) as hydrophilic organic polymeric products with sandy soil increase the soil's capacity to store water. The water stored in this way is available to plants for considerable time. Moreover, germination process, plant growth, nutrients uptake by the plants and both water and fertilizers use efficiency were beneficially increased by mixing the plant pits with hydrogels (El-Hady, 1987a; El-Hady *et al.*, 2003; El-Hady and Sedera, 2006; El-Hady and Wanas, 2006; El-Tonsi, 1997). Hydrogel networks have been reported to improve aeration and drainage of the medium (Bearce and McCollum 1977), improve market life of container grown plant (Eikhof *et al.*, 1974; Still, 1976; Bearce and McCollum, 1977), reduce the moisture stress of plants (Gehring and Lewis, 1980) and improve seed coating (Pamuk, 2004). Specht and Harvey-Jones (2000) found that less drought tolerant tree species had a much more favorable response to the application of hydrogels. *Flindersia brayleana* (Queensland maple) and *Dysoxylum muelleri* (Red bean) increased overall dry weights when hydrogels were incorporated into the growing substrate, whereas the drought tolerant species of *Flindersia australis* (Australian teak) and *Grevillea robusta* (Silky oak) showed no significant increase in overall dry weight.

There is other evidence showing that the presence of polymers prolongs the survival of plants (Callaghan *et al.*, 1988; Woodhouse and Johnson, 1991), increased

water use efficiency and dry matter production during periods of drought (Azzam, 1983 and 1985; Woodhouse and Johnson, 1991). Incorporating the hydrogel in the plant pit resulted in better plant growth, higher water and fertilizers use efficiency, especially when lower quantities of irrigation water used (El-Hady and Camilia, 2006; El-Hady *et al.*, 2009). Ahmed and Verplancke (1994) reported that an improvement in germination and biomass production of *Trifolium*, lettuce and ryegrass in dune sand with gel amendment. Seedling emergence rate and dry seedling weight in lettuce, tobacco and cotton increased in soil amended with hydrogel (Wallace and Wallace, 1986). Woodhouse and Johnson (1991) showed varying degrees of improvement in the germination and establishment of different plant species. Effects of hydrogel (Stokosorb K 410) on growth and ion relationships of salt resistant woody species, *Populus euphratica* were studied by Chen *et al.* (2003). Addition of 0.6% hydrogel to saline soil has improved seedling growth (2.7 fold higher biomass) during a period of 2 years. Root length and surface area of treated plant had 3.5 fold more than those grown in untreated soil.

Despite various beneficial effects of hydrogel addition, some studies have shown little or no benefit with hydrogel addition (Conover and Poole, 1976; James and Richards, 1986; Ingram and Yeager, 1987; Wang, 1987).

The variations in hydrogel effects and plant responses seem due to differences in the type of hydrogels and soils. Therefore, information regarding the effects of a given gel type and species responses under specific soil conditions is necessary before field applications.

The present work aims to study the conditioning effect of incorporation of amendments namely tank soil (TS), farmyard manure (FYM) and no amendment (NA)) along with different rates of Pusa hydrogel (a cross linked semi synthetic polyacrylamide copolymer) in sandy loam soil on growth, yield and water use efficiency of soybean and wheat.

4.4.3 Materials and Methods:

4.4.3.1 Experimental site and field experiments

In order to achieve the objectives, field experiments on soybean-wheat cropping system were conducted during the *kharif* and *rabi* season of 2009 and 2010 at the research farm of Indian Agricultural Research Institute, New Delhi.

4.4.3.2 Climate and soil:

The climate was semi-arid with average summer and winter temperatures ranging between 40-42°C and 5-8°C, respectively.

The soil is sandy loam (Typic Haplustept), noncalcareous, and neutral in reaction. Brief physicochemical properties of soils of the experimental site and amendments were presented in Table 4.2.1. (See research paper II).

4.4.3.3 Treatments:

In soybean season, the experiment was conducted in a split plot design with two soil amendments *i.e.*, tank soil (TS), farmyard manure (FYM) applied @ 5 t ha⁻¹ and no amendment (NA) as main treatment. Sub treatments consisted of three rates of Pusa hydrogel (a cross linked semi synthetic polyacrylamide copolymer) applied @ 5, 2.5 and 0 kg ha⁻¹. The size of the plot was 6x5 m². The number of replication for each replication was 3. In wheat, the main treatment *i.e.*, amendments were not applied but their residual effect was seen. However, the sub-treatments were similar to those of previous season.

4.4.3.4 Soil amendments:

Tank soil was collected from the bottom of a dry pond. Texture of the soil was sandy loam (60% sand, 28% clay and 12% silt) and had 0.92% organic carbon. Farm yard manure was a decomposed mixture of cattle dung and urine with straw, and had 6.29% organic carbon.

4.4.3.5 Preparation of seed bed:

Desired rate of hydrogel was mixed with 1 kg of dry sand and applied in rows at 5-7 cm soil depth along with seeds by using a manually drawn seed drill so as to cover the entire plot.

4.4.3.7 Observations:

Leaf area index during respective growth stages was monitored by canopy analyzer (LICOR-2100), and crop dry matter accumulation was determined from average biomass of 5 plant samples collected at different stages.

Depth wise (0-15, 15-30 cm) root samples were collected in soybean and wheat at flowering (70 days after sowing in soybean and 90 days after sowing in wheat) using root auger. Root samples at center were taken from center of row by placing the core auger such that center of core coincided with the base of cut plant. The cleaned root samples were scanned for measuring root length and root surface in RHIZO system and the root length density (RLD) and root surface density (RSD) were calculated. RLD was expressed as root length / volume of soil core and RSD was expressed as root surface area / volume of soil core. An area of 1 m² from each plot was harvested for determining the grain yield.

The soil moisture up to 90 cm depth in different treatments was determined using screw auger by gravimetric method and moisture content was expressed as depth units (cm). The moisture content values were then used to calculate the average moisture depletion during every irrigation cycle and the cumulated depletion during the entire crop growth cycles in both the seasons was used to calculate water use efficiency (grain yield/water used).

4.4.4 Results:

4.4.4.1 Weather conditions during crop growth and development

The daily weather data recorded at IARI observatory (adjoining the experimental plots) during the *kharif* season of 2009 and 2010 and *rabi* season of 2010 were noted for a detailed analysis. From the daily data collected, mean daily values during different weeks starting from the date of sowing were computed (in case of rainfall weekly total was computed) and analyzed to study the effect of weather factors on crop growth and development. The graphs are depicted (Fig. 3.1a, 3.1b and 3.1c) (See Material and Methods, Chapter 3) and data are presented in Appendix I, II and III.

4.4.4.1.1 Maximum temperature

The mean daily maximum temperature (on weekly basis) during *kharif* 2009 (first crop season) ranged from 30.6⁰C to 37.7⁰C, while on second season of *kharif* 2010, the mean maximum temperature were lowered by 3-4⁰C compared to first season.

During *rabi* season 2009-10, the mean maximum temperature decreased gradually from 25.5°C at 1st week after sowing (WAS) to a low of 15°C at 8th WAS and then increased to 42.2°C at 22nd WAS.

4.4.4.1.2 Minimum temperature:

The mean daily minimum temperature (on weekly basis) during *kharif* 2009 and 2010 decreased gradually from 26-27°C at 1st week after sowing (WAS) to a low of 13°C at 16th WAS, while in the *rabi* season (2009-10) mean minimum temperature were 4-7°C up to 12th week after sowing (WAS) then increased to 24.2°C at 22nd WAS.

4.4.4.1.3 Rainfall

The total amount of rainfall received during *kharif* season of 2009 was 48.96 cm while 74.94 cm was received in 2010. The total amount of rainfall received during second crop season was marginally higher by 28.96 cm and the distribution was much more congenial for seed filling. During *rabi* season 2009-10 total 14 mm rainfall occurred between 14th to 16th WAS.

4.4.4.1.4 Pan evaporation:

Daily pan evaporation ranged from 1.2 to 7 mm during *kharif* (July to November) in 2009, and 1 to 6 mm in 2010, and 1.4 to 9 mm in *rabi* 2009-10.

4.4.4.2 Leaf area index (LAI)

Leaf area index is an important parameter for the crop growth studies since it is useful in interpreting the capacity of a crop for producing dry matter in terms of the interception of radiation and amount of organic compound synthesized. Details of LAI development under different soil amendments and rates of hydrogel in soybean-wheat cropping system (Fig. 4.4.1a and 4.4.1b) are as follows:

For all the treatments, leaf area index (LAI) increased in almost similar way and reached its peak values at around 70 days after sowing (DAS) in soybean (Fig.4.4.1a). The rate of increase in leaf area as well as peak LAI were higher under FYM plots with hydrogel than rest of the treatments. In wheat also, similar results were obtained. However, peak LAI under no amendments (NA) and tank soil (TS) along with hydrogel application @ 5 kg ha⁻¹, were statistically at par.

In wheat, peak LAI was observed at 90 DAS, after which senescence of leaves started (Fig. 4.4.1b). The peak LAI significantly differed between amendment types as

well as rates of hydrogel. Maximum LAI was obtained in plots with FYM along with gel @ 5 kg ha⁻¹

4.4.4.3 Biomass:

Biomass (g m⁻²) production of the plant is the process of organic substance formation from carbohydrates, the products of photosynthesis and from small quantity of inorganic substance absorbed by roots from the soil. The timely accumulation of dry matter by the crop is important as it is followed by adequate translocation of assimilates to the sink resulting in higher yield

Maximum biomass production differed significantly among different rates of hydrogel, but no difference was observed between tank soil and no amendments treatment under a given rate of gel application. The maximum above ground biomass production in soybean was observed in FYM added soil with hydrogel applied @ 5 kg ha⁻¹ (480.91 g m⁻²) followed by no amendment treatment with hydrogel applied @ 5 kg ha⁻¹ (448 g m⁻²) (Fig. 4.4.1a and 4.4.1b).

In wheat biomass production increased by 16 and 28% with application of gel @ 2.5 and 5 kg ha⁻¹, respectively, over 1120 g m⁻² under treatment without any amendment and gel application (control). Application of FYM and tank soil increased dry biomass by 21 and 10% over control. Similarly, application of FYM along with gel application @ 2.5 and 5 kg ha⁻¹ increased it by 3 and 13% over the FYM without gel application. Whereas application of TS along with gel application @ 2.5 and 5 kg ha⁻¹ increased it by 13 and 18% over the TS without gel application

4.4.4.4 Rooting characteristics:

Analysis of root length density (RLD) (cm cm⁻³) data showed that on an average 70% of total root length were confined in upper 0-15 cm, whereas nearly 8% were below 30 cm soil layer (Fig. 4.4.2a and 4.2.1b).

Results revealed that in soybean application of FYM and TS increased RLD by 23 and 10% over 1.58 cm cm⁻³ under NA. Similarly gel application at rate of 5 and 2.5 kg ha⁻¹ increased RLD by 50 and 31 % over its value of 1.58 cm cm⁻³ under no gel treatment. Effects of amendment and gel on root surface area density (RSD) (cm² cm⁻³) (Fig. 4.4.2a) were similar to those on RLD.

In wheat application of FYM and TS increased RLD by 23 and 6% over 3.22 cm cm⁻³ under NA. In no amendment plot, application of gel @ 5 and 2.5 kg ha⁻¹ increased RLD by 26 and 16% over without gel (Fig.4.4.2b)

In FYM and TS treatment RSD increased by 76 and 10% over 0.87 cm²cm⁻³ under no amendment. However, increase in RSD with application of gel @ 5 and 2.5 kg ha⁻¹ was maximum visualized in TS, which was 150 and 76% higher than in TS without gel.

4.4.4.5 Yield:

The seed yields (q ha⁻¹) along with their statistical analysis under different treatments in both the seasons of soybean and wheat are presented in Table 4.4.1.

Analysis of grain yield data of soybean of 2009 showed that among three amendment types yield under FYM treatment was maximum and was significantly higher (50%) over 10.3 q ha⁻¹ under NA treatment. However difference between FYM and TS was statistically at par.

In no amendment treatment with gel application @ 2.5 and 5 kg ha⁻¹ yield was increased by 50 and 60% over its value of 10.3 under no amendment without gel. Statistical analysis showed significantly higher yield in both rates of gel application over control but the difference in yield between two rates of gel application was non-significant.

In tank soil treatment with gel application @ 2.5 and 5 kg ha⁻¹ yield was increased by 8 and 16% over its value of 14.22 under tank soil without gel. Statistical analysis showed significantly higher yield in TS treatment with gel application @ 5 kg ha⁻¹ over no gel treatment, but the yield between two rates of gel application was statistically at par.

In FYM treatment with gel application @ 2.5 and 5 kg ha⁻¹ yield was increased by 10 and 24% over its value of 15.23 under FYM without gel. Statistical analysis showed significantly higher yield in FYM treatment with gel application @ 5 kg ha⁻¹ over gel applied @ 2.5 kg ha⁻¹ and no gel treatment.

Similar results were obtained in second year of soybean crop growth. When the mean seed yields of two seasons were compared, it was inferred that the yields were slightly higher in second season.

In wheat (*rabi* 2009-10), the values of seed yield in FYM treated plots were 57.84, 54.7 and 52.72 q ha⁻¹; in TS treated plots were 54.88, 52.84 and 49.37 q ha⁻¹ and no amendment plots were 53.48, 50.12 and 43 q ha⁻¹ when hydrogel were applied @ 5, 2.5 and 0 kg ha⁻¹ respectively. From the yield values, it was observed that among three amendment types, seed yields were higher in FYM plot by about 23 and 7% over no amendment and tank soil. Statistical analysis showed that in all amendment types significantly higher yield in both rates of gel application over no gel but the yield between two rates of gel application was statistically *at par*.

4.4.4.6 Water use efficiency:

The soil moisture up to 90 cm depth in different treatments was determined using gravimetric method and moisture content was expressed as depth units (cm). The moisture content values were then used to calculate the average moisture depletion during every irrigation cycle and the cumulated depletion during the entire crop growth cycles in both the seasons was used to calculate water use efficiency.

In soybean 2009, water use efficiency (WUE) (kg hamm⁻¹) increased by 54 and 65% on application of gel @ 2.5 and 5 kg ha⁻¹, respectively, over 1.59 kg hamm⁻¹ under treatment without any amendment and gel application (control)) (Table 4.4.2). Application of FYM and tank soil increased WUE by 41 and 33% over control. Similarly, application of FYM along with gel application @ 2.5 and 5 kg ha⁻¹ increased it by 16 and 35% over the FYM with no hydrogel. Whereas application of TS along with gel application @ 2.5 and 5 kg ha⁻¹ increased it by 10 and 20% over the TS with no hydrogel. Similar results also were found in second season (2010) of soybean.

In *rabi* season of wheat (2009-10) it was observed that among three amendment types WUE under FYM and TS treatment were significantly higher (19 and 24%) over 13.21 kg hamm⁻¹ under NA treatment. However difference between FYM and TS were statistically *at par*.

In no amendment treatment with gel application @ 2.5 and 5 kg ha⁻¹ was increased by 12 and 19% over its value of 13.21 under no amendment without gel. Statistical analysis showed significantly higher WUE with gel application over control but the difference in WUE between two rates of gel application was non-significant.

In tank soil treatment with gel application @ 5 kg ha⁻¹ WUE was increased by 11% over its value of 16.42 under tank soil without gel. Statistical analysis showed significantly higher WUE in TS treatment with gel application @ 5 kg ha⁻¹ over no gel treatment, but the WUE between gel application @ 2.5 kg ha⁻¹ and no gel application was statistically at par. In FYM treatment with rates of gel application were statistically *at par*.

4.4.5 Discussion:

The highest LAI and biomass obtained in FYM amended with hydrogel plots could be attributed to improved uptake of water and fertilizer by soybean and wheat due to more water and nutrient availability, reduction in losses by leaching and deep percolation, better soil physical environment and deeper and denser rooting (Sow *et al.*, 1997). The above trend was similar to the field results reported by Ouchi *et al.* (1990), Sweet (1994) and Terawet Cooperation (2000) where it was mentioned that the differences in yields were due to the improved moisture retention ability of the amended soil by addition of the polymeric absorbents. Sharma (2004) stated that plants growing in hydrogel amended soil had more water available which was reflected in higher stomatal conductance and higher leaf water potential for longer period of time compared to control plants as a result frequency of irrigation may be reduced.

The higher grain yield in the second of soybean season was attributed to rainfall in a more congenial pattern during second season; therefore, no water deficit period occurred in active growing phase and pod formation stage resulted in improved grain yield production.

Higher root growth was observed in FYM along with gel application. It was mainly because of application of FYM and soil conditioner reduced mechanical impedance and improved aggregation, which increased water retention and hence more water availability during active growth stage.

Total water used by crop under no gel treatment was higher than gel treatment mainly because of higher drainage initially due to more number of drainage pores. However, among three amendment types the differences were not much.

Increase in WUE by addition of gel along with FYM application was mainly because of more availability of water in the upper root zone which resulted in efficient utilization of water, higher water uptake and better crop growth.

Studies in past have shown that mixing of super absorbent materials (hydrogel) as hydrophilic organic polymeric products with sandy soil increases the soils capacity to store water. The water stored in this way was available to plants for considerable time. Moreover, germination process, plant growth, water uptake by plants and water use efficiency was beneficially increased by mixing the plant pits in sandy soil with hydrogels (El-Hady, 1987; El- Hady and Wanes, 2006; El- Hady and Sedera, 2006; El-Hady and Camilia, 2006).

4.4.6 Conclusion:

Gel application reduced water use by reducing drainage pores and increasing retention pores so that the water availability to the plant increased and its losses through drainage were minimized. In other words the available water was efficiently utilized by growing crop which ultimately enhanced its production.

5. Discussion



In the present investigation, efficacy of Pusa hydrogel in improving soil structural stability, water availability and crop growth was assessed through lab and field studies.

In laboratory study, it was observed that soil water content (SWC) of surface soil layer remained always higher, whereas that of subsurface layer remained lower in gel treatment over no gel. This was due to more water retained by gel residing in upper surface layer, which restricted the downward movement of water.

The water release per day in sandy soil with gel application @ 0.7% (by weight) was relatively uniform throughout the entire drying period. The reason for such behavior in sandy soil was increase in adhesion between inactive sand particles and gel which reduced transmission pores and increased retention pores, hence water was released at moderate rates both at low as well as at higher suctions. In black clay soil, only during 4-7 DAW, the release was higher in gel treatment but later it reduced drastically. Here also number of water retaining pores increased with gel application and therefore water release was higher at lower suction but water release rate reduced appreciably at higher suction, probably due to increased bonding of water residing in very fine pores with soil matrix and gel. In red and alluvial soils, water release per day ranged between 1-2% during 4-14 DAW and later reduced. Here because of less reactive kaolinite and illite types of clay and their lesser amount as compared to black clay, the release rates did not reduce much at relatively higher suction.

Application of gel reduces the saturated hydraulic conductivity (K_s) significantly in all soil types. It is because of increase in retention pores and decrease in transmission pores. Results of the soil moisture characteristics curve revealed that water release per unit suction change in 0-10 kPa range (plant unavailable water) under no gel was higher as compared to with gel. But water release per unit suction change in 10-100 kPa range (plant available water) under without gel were significantly lower when compared to gel treatments in all soil types. These results have thus indicated the superiority of gel in improving the water availability to plants. Looking at above trends it could further stated that in all soil types, soil water suction of 100 kPa could be considered as the

critical limit of soil water potential as beyond it in all soils, water release per unit suction change becomes very less.

In order to confirm the suitability of gel in improving crop production in all soil types, critical soil water content (SWC corresponding to 100 kPa) during drying after initial wetting in all soil types was monitored for different gel application rates. Its magnitude for red, alluvial, sand and black under 0.7% gel treatment was 36, 30, 20 and 41%, respectively and under no gel treatment was 10.86, 14.0, 9.48 and 32%, respectively. Higher critical soil water content under gel treatment was due to increased bonding of water with soil matrix and gel which resulted in increase in very fine retention and residual pores.

Critical SWC for red, alluvial, sand and black under 0.7% gel treatment reached around 7-14, 7-14, 22 and 4-7 DAW, respectively. The result thus indicated that among all gel treated soil types, in sandy soil the critical soil water content reached after longest time interval. The above results thus clearly indicated that gel is more suitable for sandy soil as it improved the water availability for a longer period (nearly equal to 22 days which corresponded with irrigation interval for most of agricultural crops), whereas, it was found unsuitable for black soil where critical soil water content arrived early (4-7 days).

In field study effect of gel in combination with different amendment types on hydro-physical properties of alluvial sandy loam of IARI farm was studied in soybean–wheat system (2009 and 2010). Addition of FYM significantly increased transmission pores as compared to no amendment. Even though the AWSC under different amendments was same but due to lesser rate of release per unit suction change under FYM, the soil water content remained higher as compared to other treatments. It was mainly because of fact that easily decomposable fraction of FYM *i.e.*, polysaccharides and polyuronides form linkages with soil particles and water molecules and therefore restricts their rapid release. However for all amendment types, gel application reduced TP, increased Ret P, AWC and RAWC significantly. It was mainly because of the increased adhesion between inter and intra aggregate soil particles and gel. Similar to laboratory study, in field study also reduction in TP and increase in Ret P due to gel application was also reflected in significant reduction in saturated hydraulic

conductivity. Results of saturated hydraulic conductivity measured in field (K_{fs}) by Guelph permeameter showed that it was on higher side than measured in laboratory. The reason of higher value of K_{fs} was mainly because in addition to vertical movement of water, in field condition there was horizontal movement also occurred.

Soil water characteristic curve prepared at end of soybean season showed trends similar to those obtained in laboratory study. In all amendment types, with gel application, release per unit suction change in surface soil became less in 0-10 kPa range, more in 10-100 kPa (plant available water range) and very less beyond 100kPa. Hence 100 kPa was termed as critical soil water potential and corresponding soil water content was termed as critical soil water content (CSWC).

Drying pattern of soil under different treatments revealed that CSWC increased with gel application in all amendment types. Besides, CSWC was also dependent on atmospheric evaporative demand. Under low evaporative demand, by gel application CSWC arrived after a long time interval and therefore higher water release rates were obtained for longer duration. Whereas under high evaporative demand condition the beneficial effect of gel lasted for relatively shorter periods.

Effect of amendment and gel on soil physical environment was assessed by monitoring aggregate stability, mechanical impedance offered by soil, saturated hydraulic conductivity, soil water content and soil temperature during crop growth.

Structural indices showed marked improvement in stability of both macro and micro aggregates by incorporation of gel application alone or along with FYM.

Applications of gel along with FYM showed significantly lower PR mainly because of significantly higher soil water retention which acted as lubricant and reduced frictional forces and thus reduced mechanical impedance to the penetrating probe.

It was also observed that mostly throughout the day, rate of temperature change ($^{\circ}\text{C hr}^{-1}$) for all soil depths were more in treatment without hydrogel than in treatment with hydrogel application @ 5 kg ha^{-1} . This was again because of lower thermal capacity of soil with lesser SWC in no gel treatment which caused more rapid temperature increase. The temperature gradient ($^{\circ}\text{C cm}^{-1}$) was also higher in treatment without hydrogel than in treatment with hydrogel application @ 5 kg ha^{-1} . This was also

because of lower thermal conductivity of soil (because of low SWC) in no gel treatment which did not allow fast heat transport to deeper layers.

Crop growth monitored in terms of root growth, leaf area, biomass and grain yield for both soybean and wheat showed significant improvement by gel application. Among different amendment and gel combinations, highest grain yields of both soybean and wheat were obtained gel application at @5 kg ha⁻¹ treatment mainly because of more availability of water and better soil structural conditions and lower soil strength. Because of increased water availability by gel application, water use efficiency of both crops also improved significantly, which indicated the suitability of gel in rainfed areas and areas where irrigation facilities are limited. Since the gel dose is to be kept low for economic reasons, they should be applied in rows just below the seeds manually and their use should be restricted mostly in coarse texture soils and low evaporative conditions.

6. Summary and Conclusions

Laboratory as well as field studies were carried out to evaluate the efficacy of Pusa hydrogel in modifying the hydro physical environment of different soil types and also to determine its effect on water use and growth of soybean-wheat system.

The first research area of the study was to conduct a laboratory study to compare the distribution of water content in different soil types in relation to hydrogel applications.

The main treatments consisted of four different soil types viz. sand, alluvial sandy loam, red sandy loam and black clay packed in PVC columns and sub treatments consisted of three levels of gel application *i.e.*, 0.7, 0.5 and 0% (by weight). A given level of gel was mixed in upper 10 cm of soil. In all soil columns, 5 cm water was applied. For studying the drying pattern of different soil types after initial wetting, soil samples were taken at suitable interval using a core auger. The undisturbed soil of the rings of the core assembly were used for preparing soil water retention curve and soil of the core was used for determining saturated hydraulic conductivity (K_s), bulk density and gravimetric soil water content.

The results of study are summarized below:

- The result of soil water characteristic curve revealed that water release per unit suction change in 0-10 kPa range (unavailable to plants) under without gel was higher as compared to with gel .
- Water release per unit suction change in 10-100 kPa range (plant available water) under without gel were significantly lower when compared to gel treatments in all soil types.
- Water release per unit suction change pattern of all soil types, showed that it becomes very less for soil water suction >100 kPa and hence 100 kPa could be considered as the critical limit of soil water potential from water availability point of view.
- Moisture depletion pattern at low evaporative condition *i.e.*, time of arrival of critical SWC showed that for red, alluvial, sand and black soil critical SWC under 0.7% gel treatment reached around 7, 14, 22 and 4 DAW. The above results thus clearly indicated that gel was found more suitable for sandy soil

under low evaporative condition, as it improved the water availability for a longer period.

Second research area of the present investigation was to conduct a field study for characterizing soil physical environment under variable rates of hydrogel along with other soil amendments.

In *Kharif*, main treatments included FYM, tank soil (applied as an amendment @ 5 t ha⁻¹) and no amendment, and sub treatments included three rates of hydrogel *i.e.*, 5, 2.5 and 0 kg ha⁻¹ applied at 5-7 cm depth just below the seed in rows using a manual seed drill. For *rabi* experiment, amendments were not applied in the main treatment plots and they were kept as such to study the residual effect of amendment applied in the previous season. However, the sub treatments imposed were similar to those of *kharif* season.

Among various soil physical parameters studied, soil structural condition was monitored by evaluating structural indices, mechanical strength by measuring soil penetration resistance, hydraulic behavior by determining saturated hydraulic conductivity and soil thermal environment by measuring soil temperature. For studying the soil water distribution at suitable interval after irrigation soil samples were taken using screw auger and for determination soil water characteristics curve at the end of *kharif* season, soil samples were taken at using a core auger. The undisturbed soil of the rings of the core assembly was used for preparing soil water retention curve.

The results of study are summarized below:

- By addition of gel transmission porosity was reduced which was reflected in reduction in K_s on the other hand retention porosity was increased which increased both AWC and RAWC
- Among three amendment types maximum soil water content was found in FYM treatment at all soil water suction.
- 10-100 kPa, irrespective of amendment type application of gel @ 2.5 kg ha⁻¹ increased the release per unit suction change significantly but difference

between two gel application rates were non-significant. Beyond that the release per unit suction change was very less ($< 0.02\% \text{ kPa}^{-1}$).

- The amount of water locked at 1500 kPa (unavailable to the plants) by addition of gel ranged between 1-1.5% in all amendment types.
- In all amendment types, by gel application, transmission pores (TP) (drainage pores which contain water unavailable to plants) reduced significantly (5-6%), whereas retention pores (Ret P) (containing plant available water) increased by 7-9 %. Residual pores (Res P) which contain water locked in soil matrix were also increased by 1%. By addition of gel transmission porosity was reduced which was reflected in reduction in K_s , on the other hand retention porosity was increased which increased both AWC and RAWC.
- Under low pan evaporation rates ($1-1.8 \text{ mm day}^{-1}$), during drying after irrigation in FYM along with gel treatment, soil water content remains higher than its critical value for a longer period (>16 days). Whereas under high pan evaporation rates ($4-8 \text{ mm day}^{-1}$) soil water content of gel treated plots reached its critical value early.
- Irrespective of amendment type, increase in gel application rate from 0 to 2.5 kg ha^{-1} and from 2.5 to 5 kg ha^{-1} increased MWD significantly. Among, different amendment types, addition of FYM significantly improved MWD.
- Throughout the day, rate of temperature change ($^{\circ}\text{C hr}^{-1}$) for all soil depths (2, 5 and 10 cm) was more in treatment without hydrogel than in treatment with hydrogel application @ 5 kg ha^{-1} . This was because of lower thermal capacity of soil with lesser SWC in no gel treatment which caused more rapid temperature increase for same amount of heat supply.
- The temperature gradient ($^{\circ}\text{C cm}^{-1}$) was also higher in treatment without hydrogel than in treatment with hydrogel application @ 5 kg ha^{-1} . This was because of lower thermal conductivity of soil (because of low SWC) in no gel treatment which did not allow fast heat transport to deeper layers.
- Applications of gel in all amendments showed significantly lower PR mainly because of more moisture retention of soil which acts as lubricant and

reduces frictional forces and thus reduces mechanical impedance to the penetrating probe.

The third research area of the present investigation was to study the improvement in water use efficiencies and growth of soybean and wheat crops by application of hydrogel and other soil amendments. Various crop growth parameters studied were leaf area, biomass, and grain yield and root growth. Besides water use by the crops under treatments was also monitored

The results of study are summarized below:

- The seed yields, Water use efficiency and root length density were relatively higher in gel treated plots than without gel treated plots.
- The highest grain yields obtained in FYM amended with hydrogel plots could be attributed to higher uptake of water and fertilizer by both soybean and wheat because of improved soil physical environment

Following conclusions were drawn from the present investigation:

- Pusa hydrogel was found more suitable for sandy soil as it improved the water availability for a longer period (nearly equal to 22 days which corresponded with irrigation interval for most of agricultural crops), whereas, it was found unsuitable for black soil where critical soil water content arrived early (4-7 days).
- Addition of gel reduced transmission porosity which was reflected in reduction in K_s and increase in both AWC and RAWC.
- In alluvial sandy loam soils, effectiveness of gel in releasing soil water at higher rates in comparison to control is confined to shorter periods under high evaporative condition.
- That hydrogel along with FYM improved structure, lowered soil mechanical impedance, retained more soil moisture, reduced saturated hydraulic conductivity and kept the soil environment cooler as compared to control in the surface layer and thus created favourable soil physical environment for optimum crop growth.

Most important outcome of study:

From the laboratory studies following guidelines were prepared for evaluating suitability of any gel or soil conditioners in improving the water availability for a given soil type:

A given concentration of gel or soil conditioner mixed with upper few cm (8-10) of soil should be watered and a tensiometer be installed near the middle of gel layer and soil moisture tension should be recorded at regular interval till the tension reaches the maximum limit of 100 kPa. Soil moisture contents of gel and control plots should be measured at 10 and 100 kPa to compare RAWC. In case the magnitude of RAWC is higher in gel plots than in control, it will indicate that gel has improved the water available to the plant, but this result is not sufficient to draw conclusion about efficacy of gel. It is more important to note the time (days) when soil water tension of 100 kPa arrives in both the treatments. In case if it reaches after sufficiently longer time interval in gel plot which coincides with irrigation interval of the crops, it will be considered as a useful soil conditioner.

Future needs: Present investigation has also revealed several new thrust areas of research on use of hydrogel as a soil conditioner for improving the crop production. These areas are:

- Testing the performance of hydrogel for different agricultural, horticultural and vegetable crops in rain fed and irrigated areas under variable climatic conditions
- Optimizations of doses of different hydrogel formulations developed by the Institute in combination with FYM for obtaining higher economic returns
- Testing the long term effect of hydrogel on soil health.

Abstract

The present experiment entitled “ Effects of Pusa hydrogel on soil physical environment and water use efficiency in soybean-wheat cropping system” was carried out to examine the water retention and water release pattern of different kind of soil (laboratory) as well as modification on soil hydro-physical properties and crop growth under different rates of Pusa hydrogel (in field). The laboratory study was conducted in PVC columns to investigate the effect of application of hydrogel in modifying the hydraulic properties of different soil types. The main treatments consisted of four different soil types viz. sand, alluvial sandy loam, red sandy loam and black clay; and sub-treatments consisted of three levels of gel application i.e. 0.7, 0.5 and 0%. In sandy soil treated with @ 0.7% gel, the water release rates were uniform throughout the entire drying period, whereas in black clay loam, they very high initially (4-7 DAW) but reduced to < 0.5% per day afterwards. The results of soil water characteristic curve revealed that water release per unit suction change in 10-100 kPa range(plant available water) under without gel were significantly lower than in gel treatments in all soil types. The water release per unit suction change became very less for soil water suction >100 kPa and hence, 100 kPa could be considered as the critical limit of soil water suction from water availability point of view. It was further observed that under 0.7% gel treatment critical SWC (corresponding to 100 kPa) reached in red, alluvial, sand and black in 7, 14, 22 and 4 DAW. Thus, from the above study it is apparent that hydrogel is suited for sand and unsuitable for black soil.

In order to test the efficacy of Pusa hydrogel on modifying the hydro-physical properties of soil a field study was also conducted during soybean-wheat growth (2009 and 2010). Main treatment included two amendment types FYM, tank soil and no amendments applied @ 5 t ha⁻¹ and sub treatments with three rates of hydrogel i.e. 5, 2.5 and 0 kg ha⁻¹ applied at 5-7 cm depth along with seeds in rows using a manual seed drill. Results revealed that in soybean, when pan evaporation ranged between 4-7 mm day⁻¹, SWC in FYM with gel treatment reached near its critical value in 14 days, whereas, in other treatment CSWC arrived early. In wheat, during early part of growth when pan evaporation ranged between 1-1.8 mm day⁻¹, CSWC arrived in 28 days in

FYM with gel @ 5 kg ha⁻¹ treatment. However after 3rd and 4th irrigation in wheat, when pan evaporation rates ranged from 3- 7 and 5-7 mm day⁻¹, even on 13th days after irrigation the values were appreciably below (6-7 %) their CSWC. Hydrogel along with FYM significantly improved structure indices, lowered soil mechanical impedance, retained more soil moisture, reduced saturated hydraulic conductivity, kept the soil environment cooler as compared to control in the surface layer and thus created favourable soil physical environment for optimum crop growth. These beneficial effects of hydrogel lead to the higher yields and water use efficiency of crops.

मृदा भौतिकी पर्यावरण पर पूसा हाइड्रोजैल का प्रभाव तथा सोयाबीन-गेहूं फसल चक्र प्रणाली में जल उपयोग प्रभावशीलता

सारांश

“मृदा भौतिकी पर्यावरण पर पूसा हाइड्रोजैल का प्रभाव तथा सोयाबीन-गेहूं फसल चक्र प्रणाली में जल उपयोग प्रभावशीलता” शीर्षक के अंतर्गत मृदा जल-भौतिकी गुणों तथा पूसा हाइड्रोजैल की विभिन्न दरों के तहत फसल बढ़वार पर संशोधन के साथ-साथ भिन्न किस्म की मृदा (प्रयोगशाला) में जल टिकाउपन एवं जल जारी होने के पैटर्न की जांच करने के उद्देश्य से वर्तमान परीक्षण किया गया। भिन्न किस्म की मृदा के जलीय गुणों में सुधार लाने हेतु हाइड्रोजैल अनुप्रयोग के प्रभाव की जांच करने हेतु प्रयोगशाला अध्ययन को PVC कॉलम में आयोजित किया गया। चार भिन्न किस्म की मृदा यथा रेतीली, जलोढ़ रेतीली दुम्मटी, लाल रेतीली दुम्मटी तथा काली चिकनी में मुख्य उपचार किया गया और उप-उपचार के तहत 0.7, 0.5 एवं 0 % के जैल अनुप्रयोग के तीन स्तरों का इस्तेमाल किया गया। 0.7 प्रतिशत की दर से जैल के साथ उपचारित रेतीली मृदा में संपूर्ण शुष्कन अवधि के दौरान जल जारी रहने की दर एकसमान बनी रही जबकि काली चिकनी दुम्मटी मृदा में शुरू में यह दर बहुत अधिक (4-7 DAW) थी लेकिन इसके उपरान्त प्रतिदिन $< 0.5\%$ तक घटी। मृदा जल विशेषतासूचक मोड़ के परिणामों से सभी प्रकार की मृदा में जैल उपचार की तुलना में बिना जैल उपचार के तहत 10-100 kPa क्षमता (पौधे में उपलब्ध जल) में प्रति इकाई चूषण बदलाव में जल का जारी रहना पाया गया जोकि उल्लेखनीय रूप से कम था। प्रति इकाई चूषण बदलाव में जल का जारी रहना मृदा जल चूषण > 100 kPa के लिए बहुत कम हुआ अतः 100 kPa स्तर को जल उपलब्धता की दृष्टि से मृदा जल चूषण की नाजुक सीमा के तौर पर स्वीकार किया जा सकेगा। पुनः यह पाया गया कि 7, 14, 22 तथा 4 DAW में क्रमशः लाल, जलोढ़, रेतीली एवं काली मृदा में 0.7% जैल उपचार SWC(100 kPa के सादृश्य) पहुंचा। अतः उपरोक्त अध्ययन से यह प्रतीत होता है कि हाइड्रोजैल जहां रेतीली मृदा के लिए उपयुक्त है वहीं वह काली मृदा के लिए अनुपयुक्त है।

मृदा के जल-भौतिकी गुणों में सुधार करने हेतु पूसा हाइड्रोजैल की प्रभावशीलता का परीक्षण करने के क्रम में वर्ष 2009 एवं 2010 के दौरान सोयाबीन-गेहूं बढ़वार में एक खेत अध्ययन का आयोजन किया गया। मुख्य उपचार में तीन संशोधन नामतः गोबर की खाद (FYM) तालाब की मृदा तथा 5 टन/हैक्टर की दर पर संशोधन रहित उपचार नहीं का उपयोग किया जाना शामिल था वहीं गौण उपचार के अंतर्गत हाथ से चलने वाली सीड ड्रिल का उपयोग करते हुए पंक्तियों में 5-7 सें.मी. गहराई पर 5, 2.5 एवं 0 कि.ग्रा./हैक्टर हाइड्रोजैल की तीन दरों का उपयोग किया जाना शामिल था। परिणामों से पता चला कि सोयाबीन में पटल वाष्पन दर 4-7 मि.मी./दिन होने पर जैल उपचार के साथ गोबर की खाद में SWC 14 दिनों में अपनी नाजुक स्थिति में पहुंच गई जबकि अन्य उपचारों में CSWC अगेती हुआ। बढ़वार की प्रारंभिक स्थिति में पटल वाष्पन दर 1-1.8 मि.मी./दिन रहने पर 5 कि.ग्रा./हैक्टर की दर से जैल उपचार के साथ गोबर की खाद में CSWC 28 दिन में आया। हालांकि, गेहूं में तीसरी तथा चौथी सिंचाई के उपरांत जबकि पटल वाष्पन दर 3-7 एवं 5-7 मि.मी./दिन थी, यहां तक कि सिंचाई के 13 दिन पश्चात् भी मान अपनी CSWC से पर्याप्त स्तर (6-7 प्रतिशत) तक निम्न थे। ऊपरी सतह पर नियंत्रण की तुलना में गोबर की खाद के साथ मिलकर हाइड्रोजैल से ढांचा अक्षांक में उल्लेखनीय सुधार हुआ, मृदा यांत्रिकी बाधा कम हुई, मृदा में कहीं अधिक नमी बनी रही, संतृप्त जलीय चालकता घटी तथा मृदा पर्यावरण ठंडा बना रहा और अंततः इससे अनुकूलनतम फसल बढ़वार के लिए अनुकूल मृदा भौतिकी पर्यावरण पैदा हुआ। हाइड्रोजैल के इन लाभकारी प्रभावों से कहीं अधिक पैदावार और फसलों की जल उपयोग प्रभावशीलता को बढ़ावा मिलेगा।

Table 3.1a: Site characteristic of different soil types

Site	Classification
Sandy	Mixed Hyperthermic, family of Typic Torripsamment.
Alluvial	Coarse loamy, illitic, family of Typic Haplustept
Red	Fine loamy, Kaolinitic, Hyperthermic, family of Ustic Paleustalfs
Black	Fine Smectitic, Hyperthermic, family of Typic Haplustert.

Table 3.1b: The physical and chemical characteristics of different soil types

Soil type	Relative proportion			Soil texture	EC (mmohs cm ⁻¹)	pH	OC (%)
	Sand %	Silt %	Clay %				
Sandy	92	2	6	Sandy	0.11	7.01	0.27
Alluvial	66	9	25	Sandy loam	0.15	6.25	0.30
Red	64	8	28	Sandy loam	0.05	6.52	0.29
Black	40	20	40	Clay	0.18	5.35	0.31

Table: 3.2a. Physico-chemical properties of the experimental soil

Depth (cm)	Bulk Density (g cm ⁻³)	pH	EC (mmohs cm ⁻¹)	Organic C (per cent)
0-15	1.42	6.25	0.15	0.30
15-30	1.6	6.9	0.25	0.24
30-60	1.65	7.6	0.25	0.18

Table: 3.2b. Physical properties of the experimental soil

Depth (cm)	Particle Size Distribution (per cent)			Saturated Hydraulic conductivity (cm hr ⁻¹)	Soil Moisture Retention (per cent)	
	sand	silt	clay		0.33 MPa	1.5 MPa
0-15	66	9	25	1.15	23.71	5.74
15-30	74.4	10.7	14.9	0.8	21.1	5.8

Table: 3.3. Treatments of the experiment

Treatment	Treatment Name	Specification
T ₁	TS+5G	Tank soil @ 5t ha ⁻¹ + hydrogel @ 5kg ha ⁻¹
T ₂	TS+2.5G	Tank soil @ 5t ha ⁻¹ + hydrogel @ 2.5kg ha ⁻¹
T ₃	TS+0G	Tank soil @ 5t ha ⁻¹ +hydrogel @ 0 kg ha ⁻¹
T ₄	NA+5G	No amendments + hydrogel @ 5kg ha ⁻¹
T ₅	NA+2.5G	No amendments + hydrogel @ 2.5kg ha ⁻¹
T ₆	NA+0G	No amendments + hydrogel @ 0 kg ha ⁻¹
T ₇	FYM+5G	Farmyard manure @ 5t ha ⁻¹ + hydrogel @ 5kg ha ⁻¹
T ₈	FYM+2.5G	Farmyard manure @ 5t ha ⁻¹ + hydrogel @ 2.5kg ha ⁻¹
T ₉	FYM+0G	Farmyard manure @ 5t ha ⁻¹ + hydrogel @ 0 kg ha ⁻¹

Table 4.3.2. Bulk density (g cm^{-3}) under various gel application rates in different soil amendment types after harvest of second season of soybean 2010.

Treatments	Bulk density (g cm^{-3})
TS+5G	1.42
TS+2.5G	1.42
TS+0G	1.45
NA+5G	1.43
NA+2.5G	1.44
NA+0G	1.48
FYM+5G	1.43
FYM+2.5G	1.43
FYM+0G	1.44

Table 4.1.1. Soil water content change per unit change in soil water suction [(%, v/v) / kPa] in different regions of soil water characteristics curve

SWS (kPa)	Sandy			Alluvial			Red			Black		
	G 0.7%	G 0.5%	G 0%	G 0.7%	G 0.5%	G 0%	G 0.7%	G 0.5%	G 0%	G 0.7%	G 0.5%	G 0%
0-10	1.0	1.04	1.1	0.76	0.77	0.78	0.30	0.50	0.53	0.24	0.41	0.57
10-100	0.44	0.36	0.11	0.26	0.29	0.16	0.36	0.29	0.17	0.34	0.27	0.18
100-300	0.01	0.01	<0.005	0.01	0.02	0.02	0.05	0.03	<0.02	0.01	0.03	<0.005
300-1500	rates were very less											

Table 4.1.2. Mid point moisture (MPM), median pore diameter (d_m) and moisture release index (I_m) under various gel application rates in different soil types

	Sandy			Alluvial			Red			Black		
	G 0.7%	G 0.5%	G 0%	G 0.7%	G 0.5%	G 0%	G 0.7%	G 0.5%	G 0%	G 0.7%	G 0.5%	G 0%
MPM (%v/v)	40.1	34.9	17.5	38.4	36.1	21.8	40.1	34.4	19.5	53.2	49.0	41.0
d_m (μm)	10.0	10.71	15.79	6.82	11.11	12.50	4.41	7.14	13.04	6.82	8.11	8.82
(I_m) (v/v) %/ kPa	0.33	0.40	0.40	0.10	0.33	0.40	0.13	0.33	0.50	0.40	0.50	0.33

Table 4.1.3. Pore size distribution, readily plant available and plant available water capacity under various gel application rates in different soil types.

	Sandy			Alluvial			Red			Black		
	G 0.7%	G 0.5%	G 0%	G 0.7%	G 0.5%	G 0%	G 0.7%	G 0.5%	G 0%	G 0.7%	G 0.5%	G 0%
TP (μm) %	10.02 ^a	10.37 ^a	10.95 ^a	7.60 ^b	7.74 ^b	7.80 ^b	3.05 ^{de}	5.01 ^c	5.26 ^c	2.36 ^e	4.06 ^{cd}	5.65 ^c
Ret P (μm) %	50.84 ^a	46.48 ^b	15.01 ⁱ	37.36 ^{de}	35.48 ^{ef}	22.26 ^g	47.63 ^b	39.45 ^{cd}	18.17 ^h	40.59 ^c	32.96 ^f	20.27 ^{gh}
Res P (μm) %	9.66 ^e	6.47 ^{fg}	4.49 ^g	15.94 ^c	14.52 ^c	6.74 ^f	14.77 ^c	12.15 ^d	7.83 ^{ef}	31.72 ^a	30.47 ^a	28.05 ^b
AWC% (v/v) 30-1500 kPa	29.59 ^{bc}	28.27 ^c	9.52 ^g	23.14 ^d	18.31 ^e	12.97 ^f	31.1 ^b	28.1 ^c	6.97 ^h	35.92 ^a	22.77 ^d	14.97 ^f
RAWC % (v/v) 30-100 kPa	39.57 ^a	32.42 ^b	10.02 ^f	23.14 ^d	25.06 ^{cd}	14.3 ^e	32.16 ^b	26.17 ^c	15.14 ^e	30.58 ^b	24.37 ^{cd}	16.29 ^e

a-i values followed by different letters in the same row are significantly different at the P < 0.05 level. In LSD comparison test.

Table 4.1.4. Correlations among various hydraulic parameters

	TP	AWC	Res P	RAWC	Ret P	MPM	d _m	I _m	K _s
TP	1.00								
AWC	-0.32	1.00							
ResP	-0.70	0.36	1.00						
RAWC	-0.03	0.86	0.16	1.00					
Ret P	-0.09	0.91	0.09	0.94	1.00				
MPM	-0.53	0.78	0.83	0.66	0.62	1.00			
d _m	0.68	-0.77	-0.59	-0.52	-0.65	-0.79	1.00		
I _m	0.04	-0.36	0.04	-0.19	-0.43	-0.20	0.58	1.00	
K _s	0.69	-0.45	-0.74	-0.24	-0.31	-0.73	0.78	0.35	1.00

Table 4.2.1. The physical and chemical characteristics of the experimental soils and amendments

Soil type	Relative proportion			Soil texture	EC (mmohs cm ⁻¹)	pH	OC (%)
	Sand %	Silt %	Clay %				
Alluvial	66	9	25	Sandy loam	0.15	6.25	0.30
Tank soil	60	12	28	Sandy loam	1.62	7.54	0.92
FYM	-	-	-		-	-	6.29

Table 4.2.3. Pore size distribution, readily plant available (RAWC), and plant available water capacity (AWC), moisture mid point (MPM) and pore median diameter (d_m) under various gel application rates in different soil amendment types

	No amendments			Tank soil			FYM		
	Gel 0	Gel 2.5	Gel 5	Gel 0	Gel 2.5	Gel 5	Gel 0	Gel 2.5	Gel 5
TP(μm) %	19.61 ^b	13.81 ^f	13.26 ^f	18.77 ^b	16.05 ^{de}	15.64 ^e	22.94 ^a	17.51 ^c	17.04 ^{cd}
Ret P(μm) %	21.47 ^d	28.13 ^b	28.78 ^{ab}	20.37 ^{df}	23.71 ^c	28.01 ^b	19.40 ^e	29.13 ^{ab}	29.91 ^a
Res P(μm)	5.74 ^e	6.58 ^c	7.43 ^{ab}	5.78 ^{de}	6.81 ^{bc}	7.11 ^{abc}	6.75 ^{cd}	7.39 ^{ab}	7.63 ^a
AWC % (v/v)	17.97 ^c	19.14 ^{bc}	20.68 ^{ab}	17.91 ^c	18.95 ^c	20.60 ^{ab}	17.89 ^c	20.58 ^{ab}	22.04 ^a
RAWC % (v/v)	14.45 ^c	20.73 ^a	20.54 ^a	13.19 ^{cd}	16.75 ^b	20.05 ^a	12.17 ^d	21.02 ^a	20.79 ^a
MPM % (v/v)	26.28	27.55	28.45	25.35	26.69	28.93	27.92	30.71	31.11
d_m (μm)	25.00	21.43	20.00	25.00	21.43	20.00	27.27	22.22	20.69

a-f values followed by different letters in the same row are significantly different at the $P < 0.05$ level. In LSD comparison test.

Table 4.2.4. Saturated hydraulic conductivity (K_s) under various gel application rates in different soil amendment types

	No amendments			Tank soil			FYM		
	Gel 0	Gel 2.5	Gel 5	Gel 0	Gel 2.5	Gel 5	Gel 0	Gel 2.5	Gel 5
$K_s(kharif)$ cm day ⁻¹	22.54 ^b	11.07 ^e	7.39 ^f	15.12 ^{cd}	9.94 ^e	7.01 ^f	29.31 ^a	15.94 ^c	13.82 ^d
$K_s(rabi)$ cm day ⁻¹	20.39 ^b	9.78 ^e	6.87 ^f	13.66 ^{cd}	9.51 ^e	5.86 ^f	26.70 ^a	14.03 ^c	12.43 ^d

a-f values followed by different letters in the same row are significantly different at the $P < 0.05$ level. In LSD comparison test.

Table 4.3.1a. Mean weight diameter (MWD), Water stable structural unit (WSSU) and Structural coefficient (Cr) under various gel application rates in different soil amendment types after harvest of soybean 2009

	No amendments			Tank soil			FYM		
	Gel 0	Gel 2.5	Gel 5	Gel 0	Gel 2.5	Gel 5	Gel 0	Gel 2.5	Gel 5
MWD(mm)	0.45 ^e	0.61 ^d	0.76 ^c	0.47 ^e	0.65 ^d	0.69 ^{cd}	0.77 ^{bc}	0.86 ^{ab}	0.95 ^a
WSSU %	16.85 ^f	24.59 ^{cd}	26.2 ^{bcd}	20.4 ^e	24.1 ^d	27.4 ^{abc}	24.4 ^d	28.4 ^{ab}	29.15 ^a
Cr	0.24 ^e	0.33 ^{bc}	0.36 ^{ab}	0.26 ^{de}	0.32 ^{bc}	0.39 ^a	0.29 ^{cde}	0.31 ^{bcd}	0.40 ^a

a-f values followed by different letters in the same row are significantly different at the P <0.05 level. In LSD comparison test.

Table 4.3.1b. Mean weight diameter (MWD), Water stable structural unit (WSSU) and Structural coefficient (Cr) under various gel application rates in different soil amendment types after harvest of wheat 2009-10

	No amendments			Tank soil			FYM		
	Gel 0	Gel 2.5	Gel 5	Gel 0	Gel 2.5	Gel 5	Gel 0	Gel 2.5	Gel 5
MWD(mm)	0.54 ^g	0.74 ^e	0.85 ^{cd}	0.66 ^f	0.79 ^{de}	0.91 ^{bc}	0.94 ^b	1.07 ^a	1.09 ^a
WSSU %	23.95 ^e	29.85 ^{bc}	26.4 ^{de}	32.31 ^{ab}	28.05 ^{cd}	30.7 ^{bc}	27.95 ^{cd}	31.95 ^b	35.25 ^a
Cr	0.60 ^d	0.66 ^d	0.80 ^c	0.78 ^c	0.86 ^{bc}	0.99 ^a	0.66 ^d	0.90 ^b	1.05 ^a

a-g values followed by different letters in the same row are significantly different at the P <0.05 level. In LSD comparison test.

Table. 4.4.1. Yield (q ha⁻¹) of soybean (2009 and 2010) and wheat (2009-10) under various gel application rates in different soil amendment type

	No amendments			Tank soil			FYM		
	Gel 0	Gel 2.5	Gel 5	Gel 0	Gel 2.5	Gel 5	Gel 0	Gel 2.5	Gel 5
Soybean (2009)	10.3 ^d	15.55 ^{bc}	16.52 ^b	14.22 ^c	15.38 ^{bc}	16.59 ^b	15.23 ^{bc}	16.74 ^b	18.84 ^a
Soybean (2010)	12.18 ^e	15.65 ^{cd}	16.54 ^c	15.31 ^d	16.56 ^c	17.83 ^b	16.13 ^{cd}	18.03 ^{ab}	18.99 ^a
Wheat (2009-10)	43.0 ^c	50.12 ^{bc}	53.48 ^{ab}	49.37 ^{bc}	52.84 ^{ab}	54.88 ^{ab}	52.72 ^{ab}	54.7 ^{ab}	57.84 ^a

a-e values followed by different letters in the same row are significantly different at the P <0.05 level. In LSD comparison test.

Table. 4.4.2. Water use efficiency (kg / ha mm) of soybean (2009 and 2010) and wheat (2009-10) under various gel application rates in different soil amendment type

	No amendments			Tank soil			FYM		
	Gel 0	Gel 2.5	Gel 5	Gel 0	Gel 2.5	Gel 5	Gel 0	Gel 2.5	Gel 5
Soybean (2009) (kg / ha mm)	1.59 ^f	2.45 ^{bcd}	2.63 ^b	2.13 ^e	2.35 ^{cde}	2.57 ^{bc}	2.25 ^{de}	2.62 ^b	3.05 ^a
Soybean (2010) (kg / ha mm)	1.36 ^e	1.78 ^{cd}	1.90 ^c	1.75 ^d	1.90 ^c	2.08 ^{ab}	1.84 ^{cd}	2.07 ^b	2.21 ^a
Wheat (2009-10) (kg / ha mm)	13.21 ^c	14.81 ^{bc}	15.68 ^b	16.42 ^{ab}	16.85 ^{ab}	18.25 ^a	15.69 ^b	15.98 ^{ab}	16.37 ^{ab}

a-f values followed by different letters in the same row are significantly different at the P <0.05 level. In LSD comparison test.

Table 4.3.2. Saturated hydraulic conductivity (K_s) (cm day^{-1}) under various gel application rates in different soil amendment types

	No amendments			Tank soil			FYM		
	Gel 0	Gel 2.5	Gel 5	Gel 0	Gel 2.5	Gel 5	Gel 0	Gel 2.5	Gel 5
$K_s(\text{Kharif})$ cm day^{-1}	22.54 ^b	11.07 ^e	7.39 ^f	15.12 ^{cd}	9.94 ^e	7.01 ^f	29.31 ^a	15.94 ^c	13.82 ^d
$K_s(\text{rabi})$ cm day^{-1}	20.39 ^b	9.78 ^e	6.87 ^f	13.66 ^{cd}	9.51 ^e	5.86 ^f	26.70 ^a	14.03 ^c	12.43 ^d

a-f values followed by different letters in the same row are significantly different at the $P < 0.05$ level. In LSD comparison test.

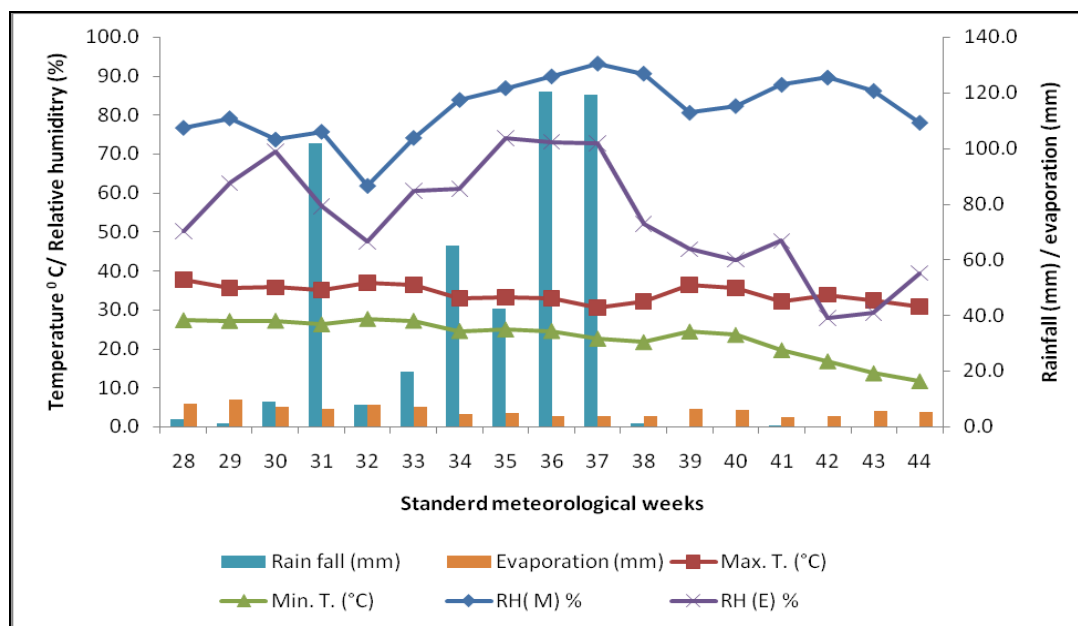


Fig. 3.1a. Mean daily weather parameters during standard weeks of the growing period of soybean (2009).

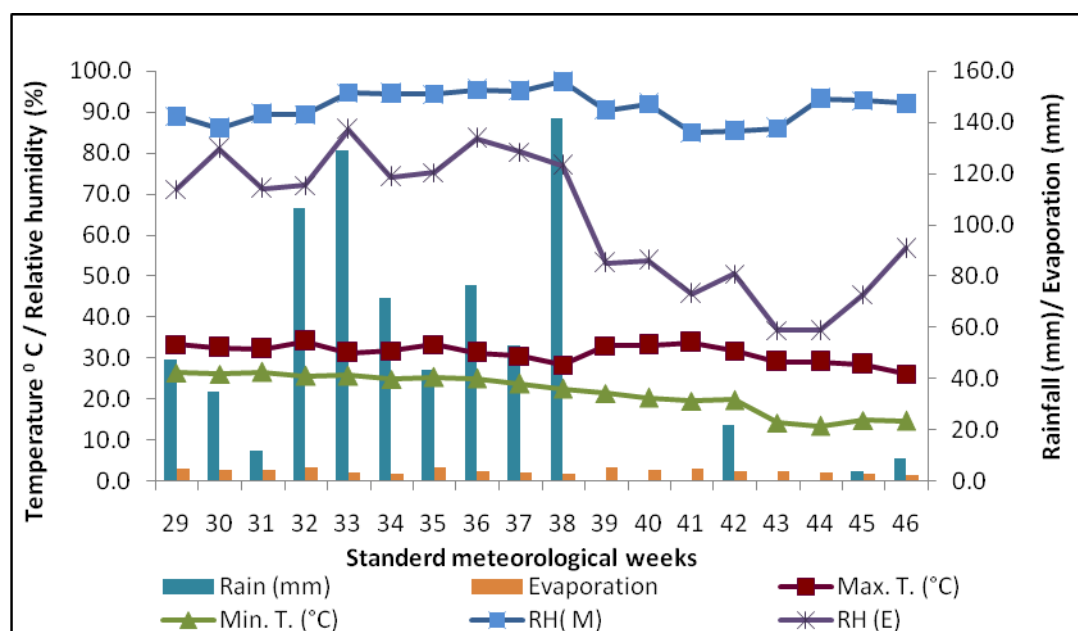


Fig. 3.1b. Mean daily weather parameters during standard weeks of the growing period of soybean (2010).

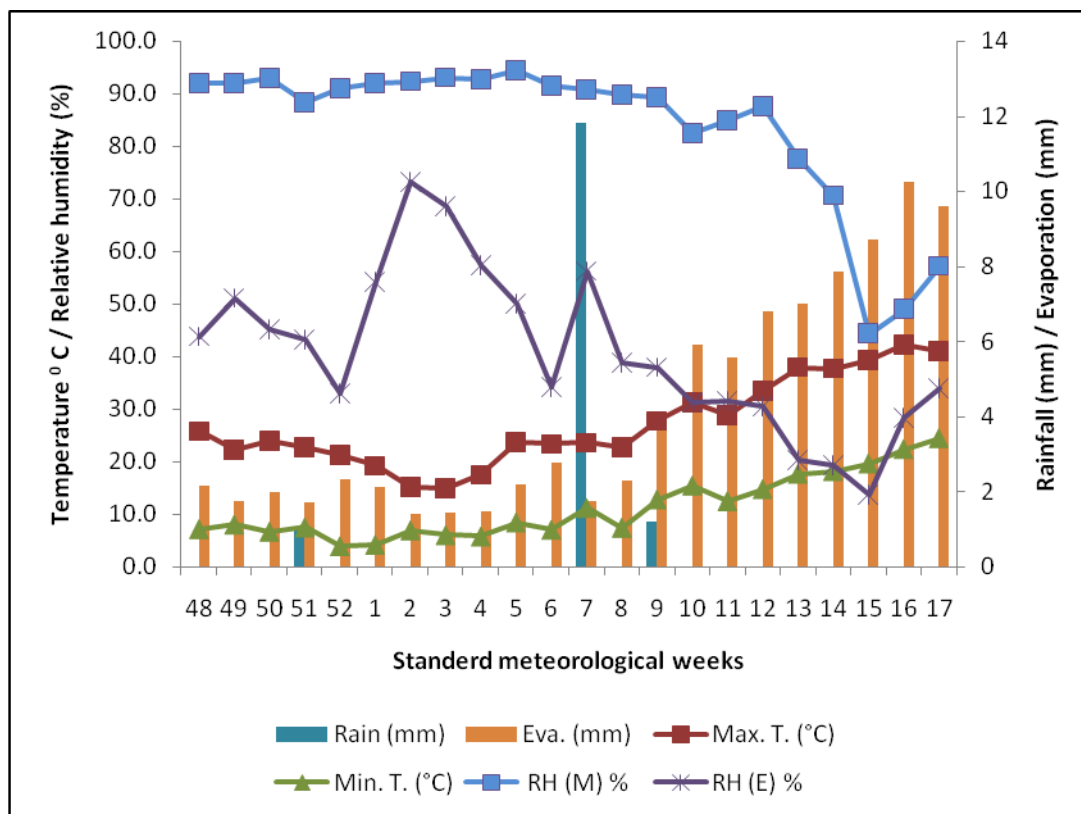


Fig. 3.1c. Mean daily weather parameters during standard weeks of the growing period of wheat (2009-10).

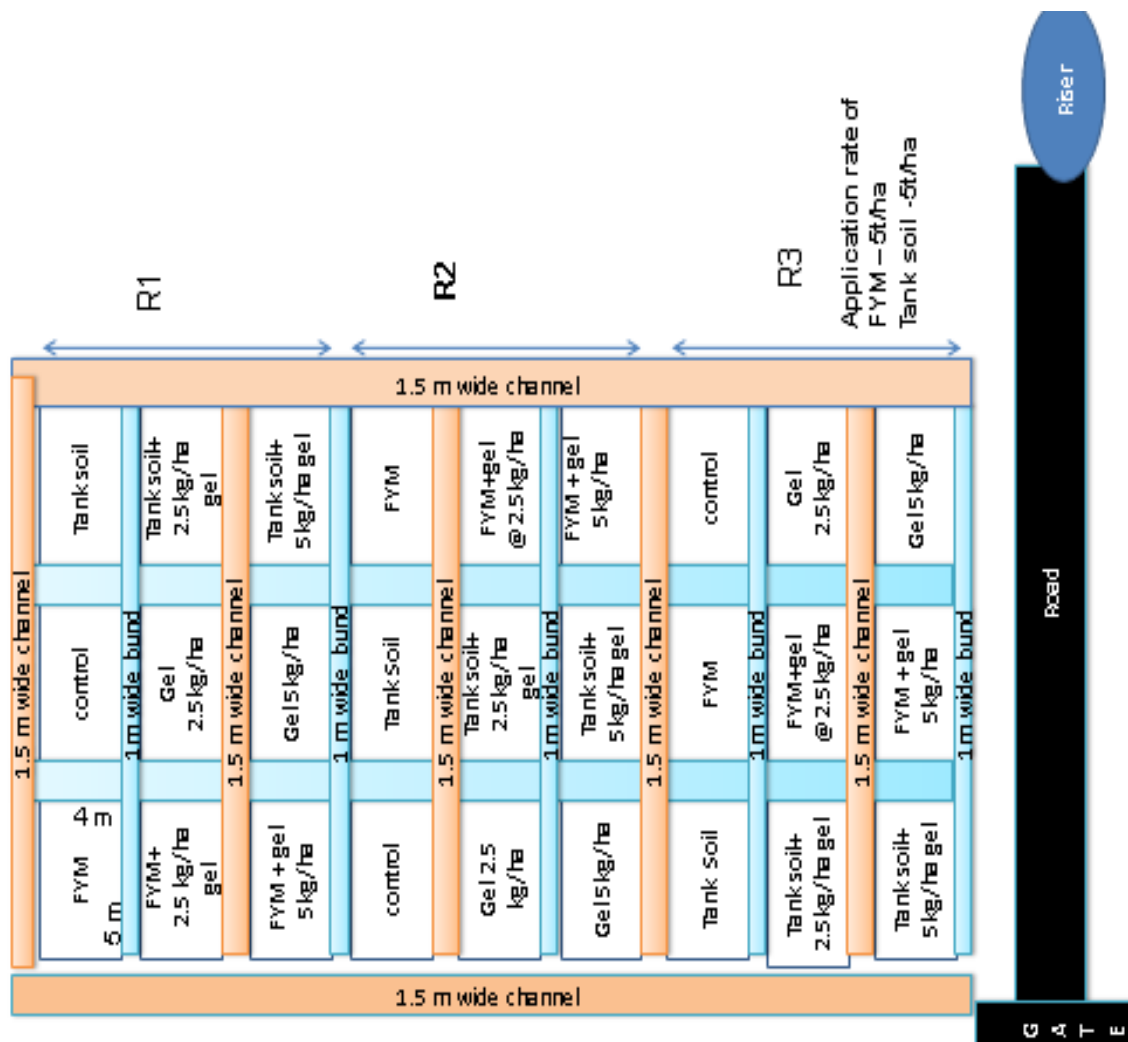


Fig. 3.2. Layout of the experimental plots at IARI, New Delhi

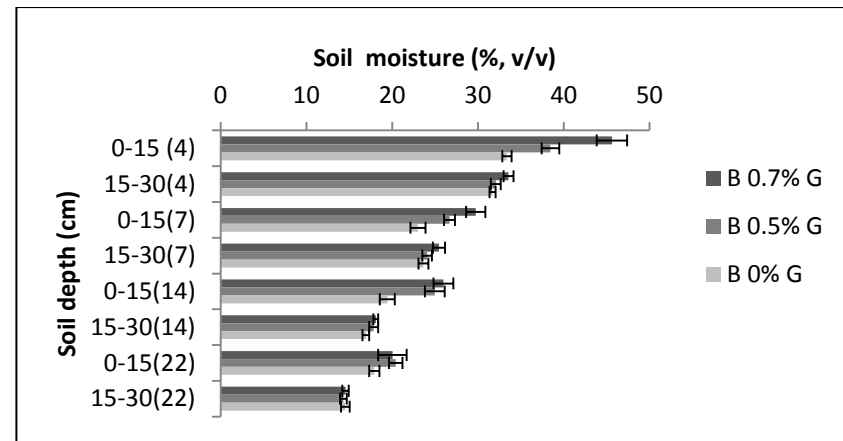
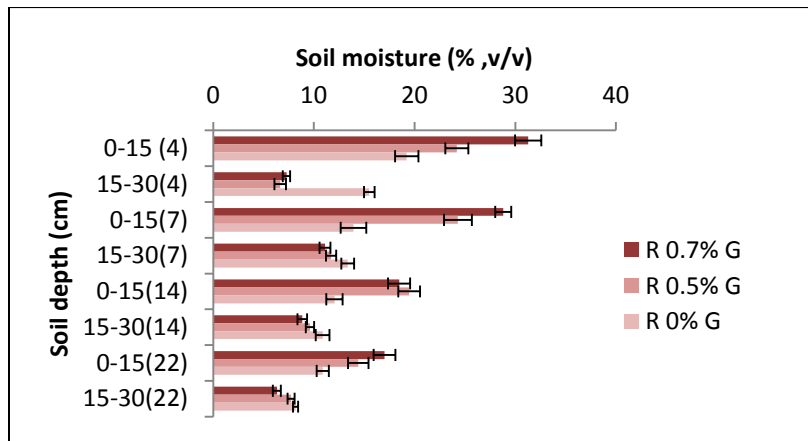
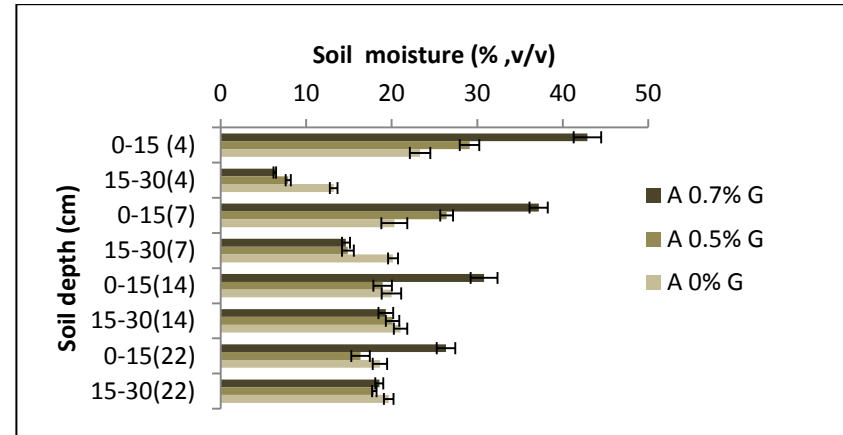
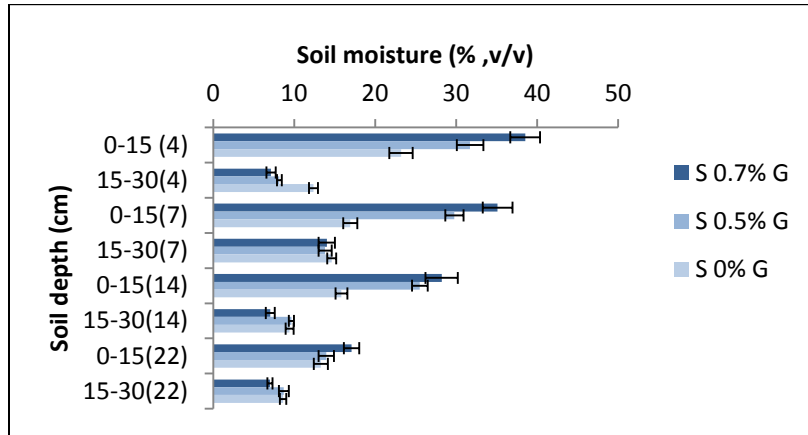


Fig. 4.1.1. Moisture distribution pattern at 0-15 and 15-30 cm depths of different types of soil packed in PVC columns under variable gel application rates on different days (given in bracket of vertical axis). (S: sandy; A: alluvial; R: red; B: black and G: hydrogel)

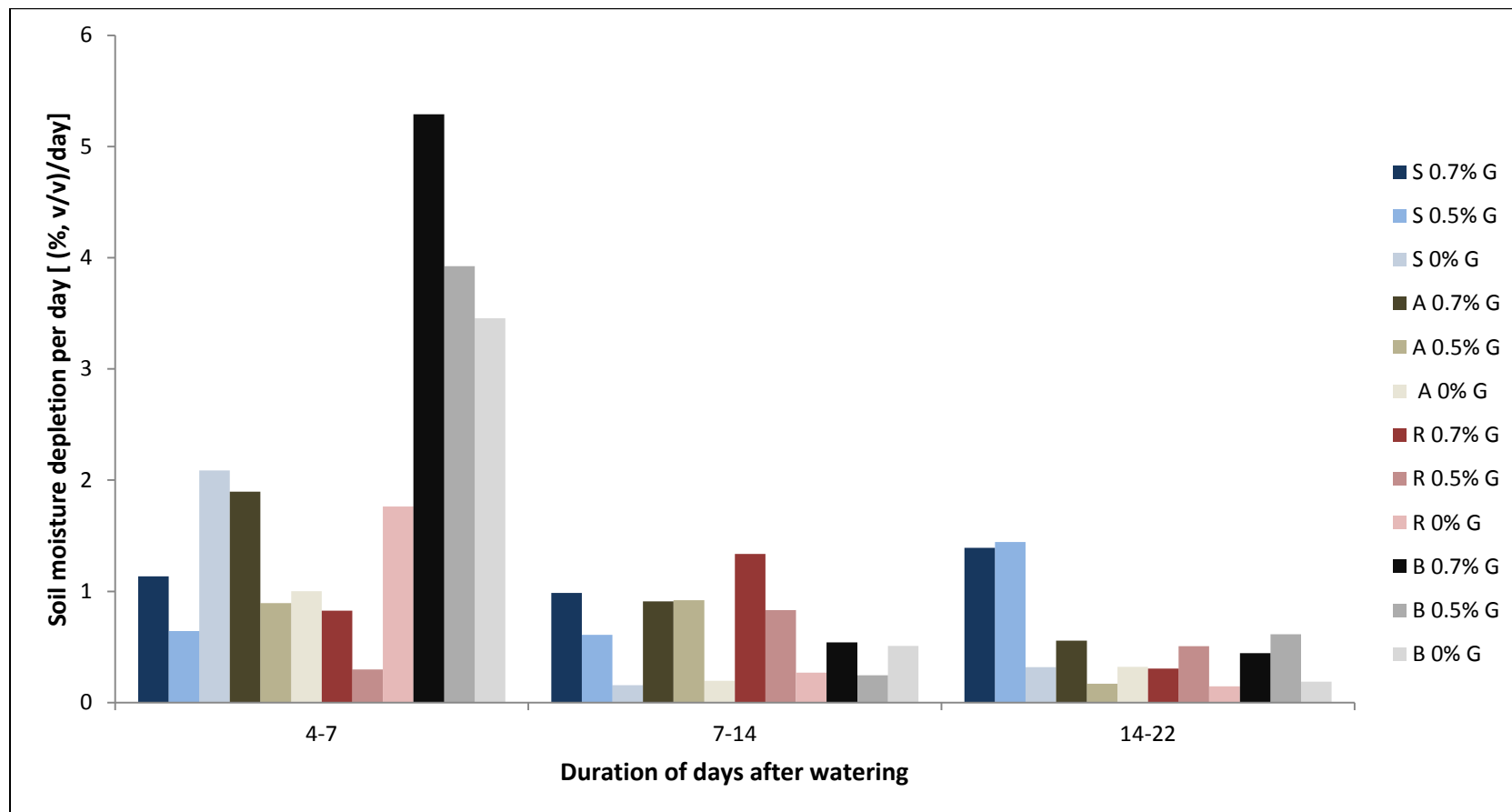


Fig.4.1.2. Depletion of moisture per day from 0-15 cm layer in soils of different types in PVC columns under variable gel application rates during different periods of drying (S: sandy; A: alluvial; R: red; B: black and G: hydrogel)

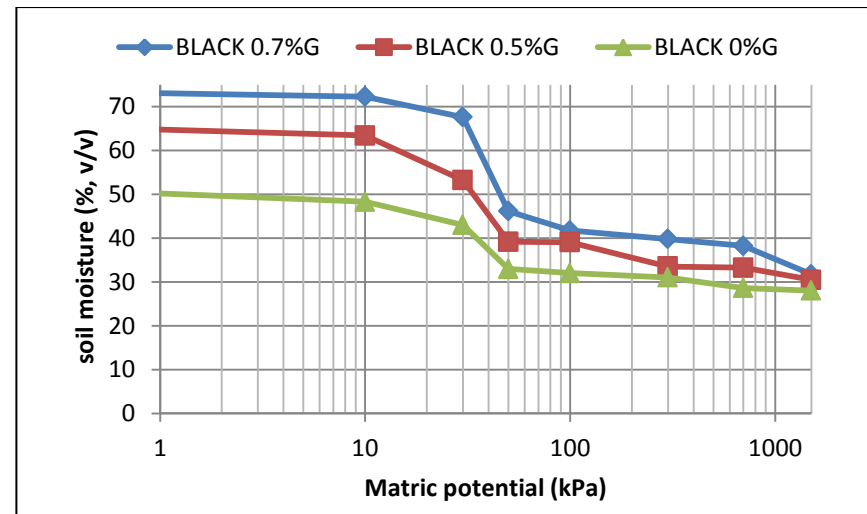
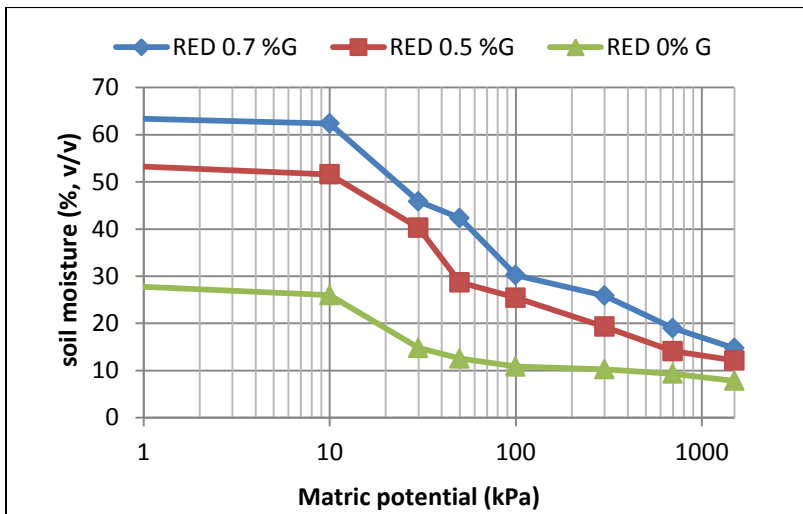
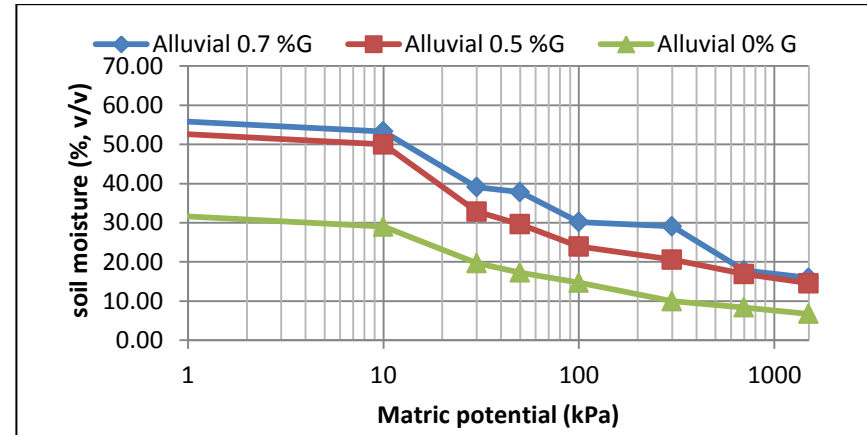
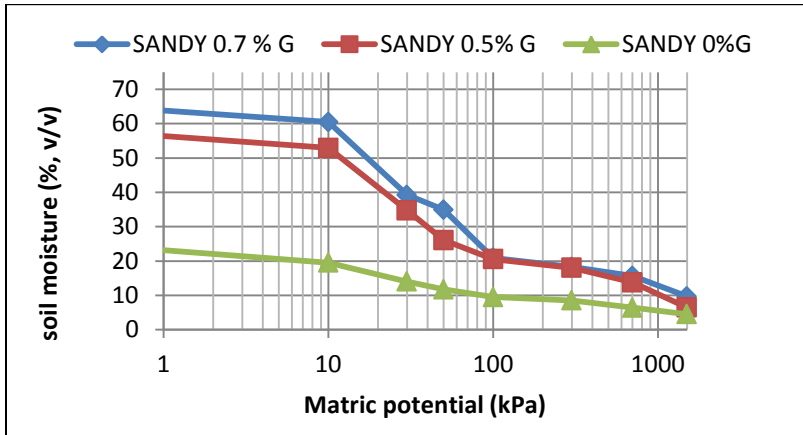


Fig. 4.1.3. Soil moisture characteristic curves of sandy, alluvial, red and black soil under different gel application rates.

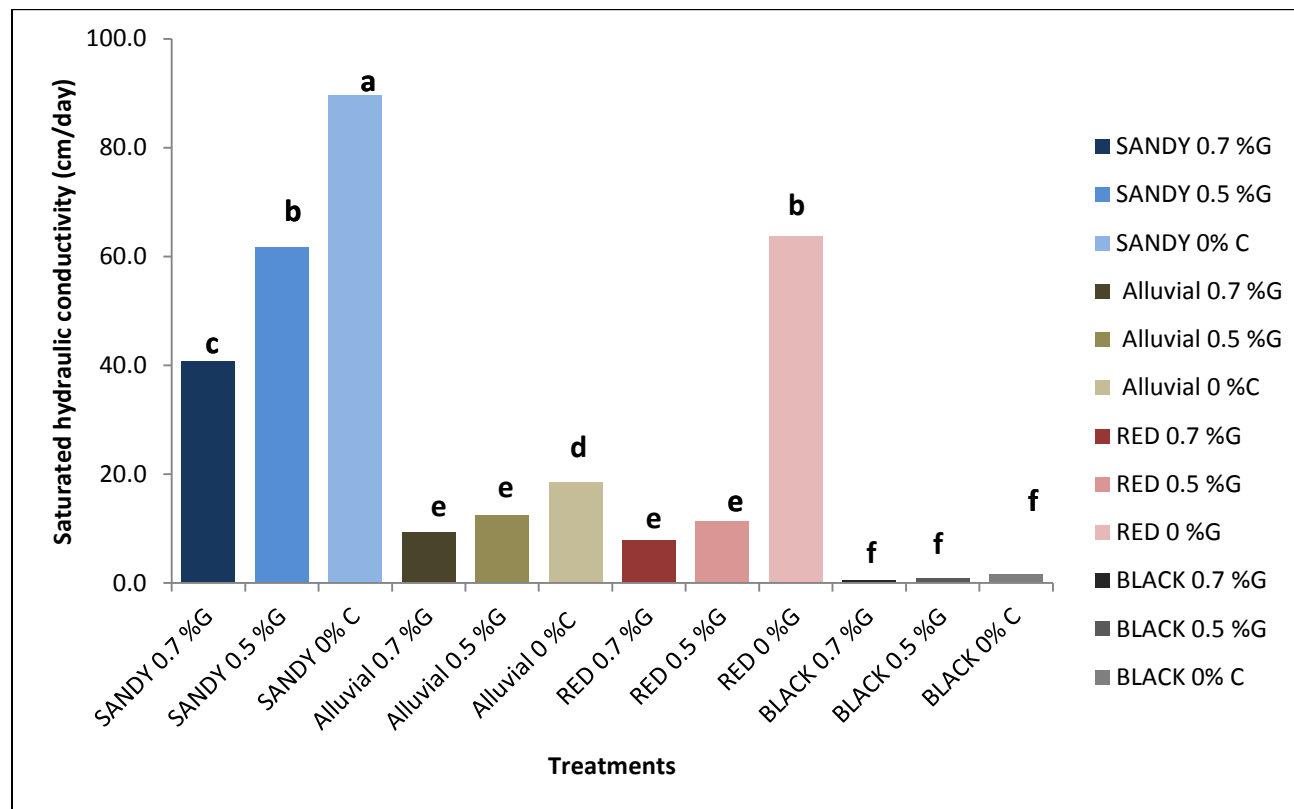


Fig. 4.1.4. Saturated hydraulic conductivity (K_s) of different soil types under different rates of gel application.

(a-f values followed by different letters are significantly different at the $P < 0.05$ level. In LSD comparison test)

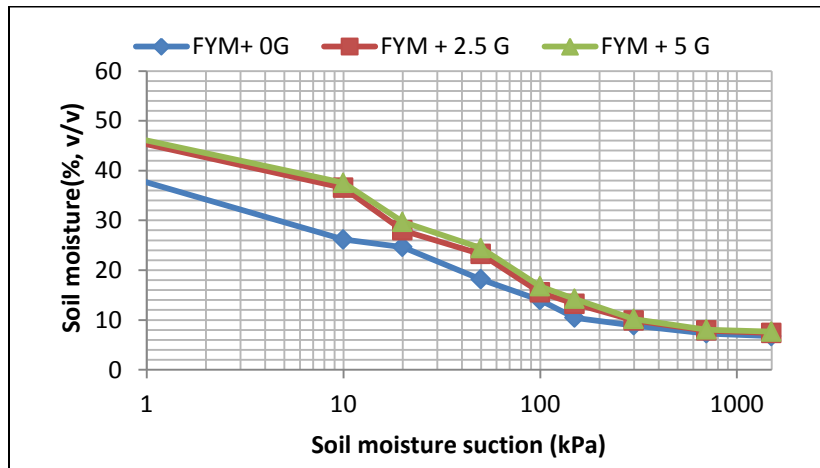
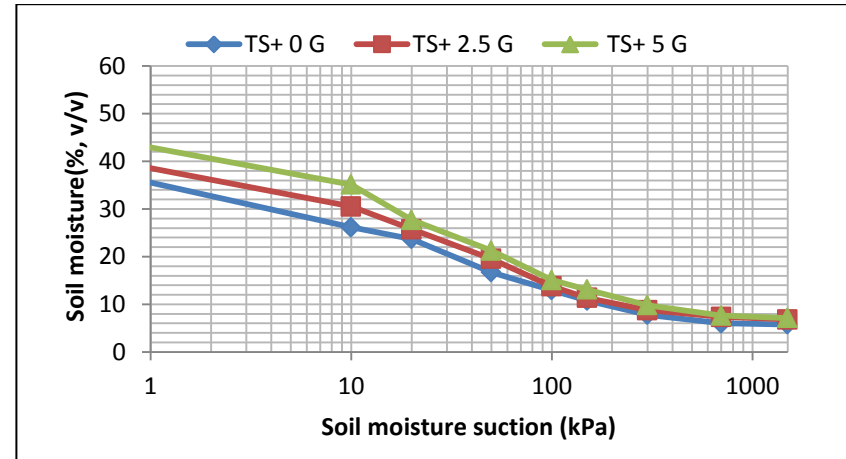
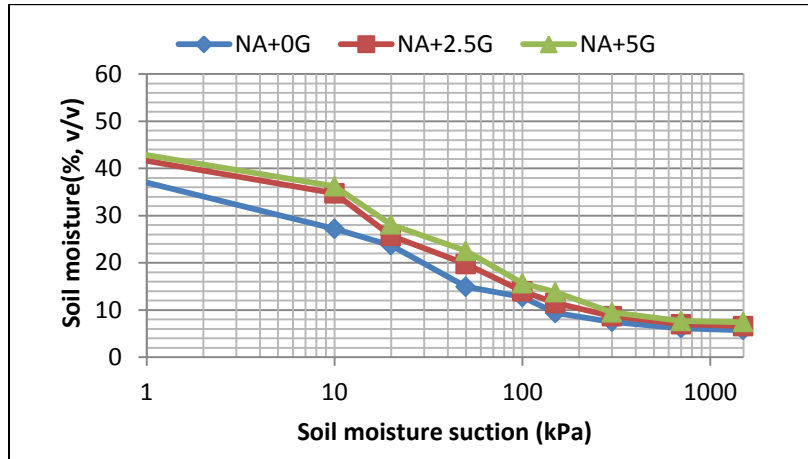


Fig. 4.2.1. Soil moisture characteristic curves of different amendments in sandy loam soil under varying rates of hydrogel application (NA: No amendment; TS: Tank soil; FYM: Farmyard manure and G: hydrogel)

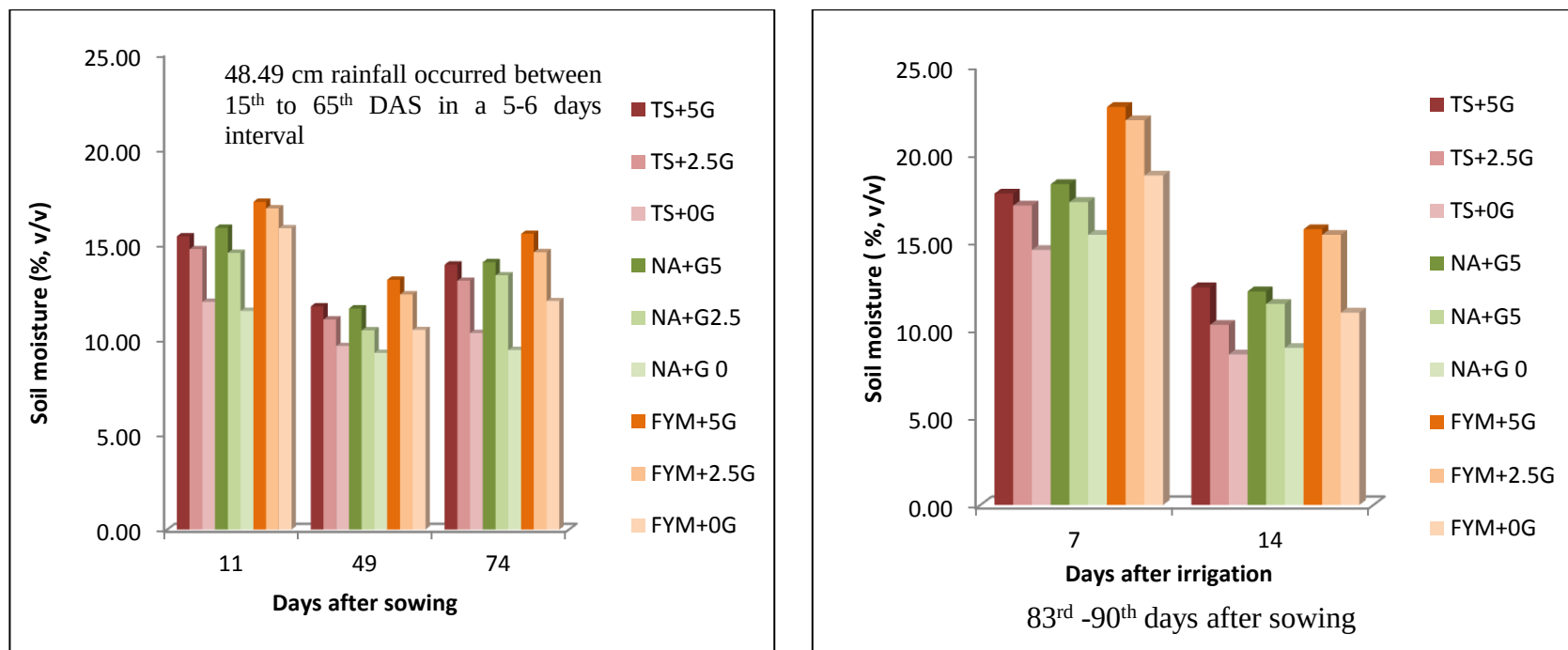


Fig. 4.2.2a. Soil moisture content (upto 15 cm soil layer) of different amendments under varying rates of hydrogel application during the *kharif* season (July – October) 2009. (NA: No amendment; TS: Tank soil; FYM: Farmyard manure and G: hydrogel)

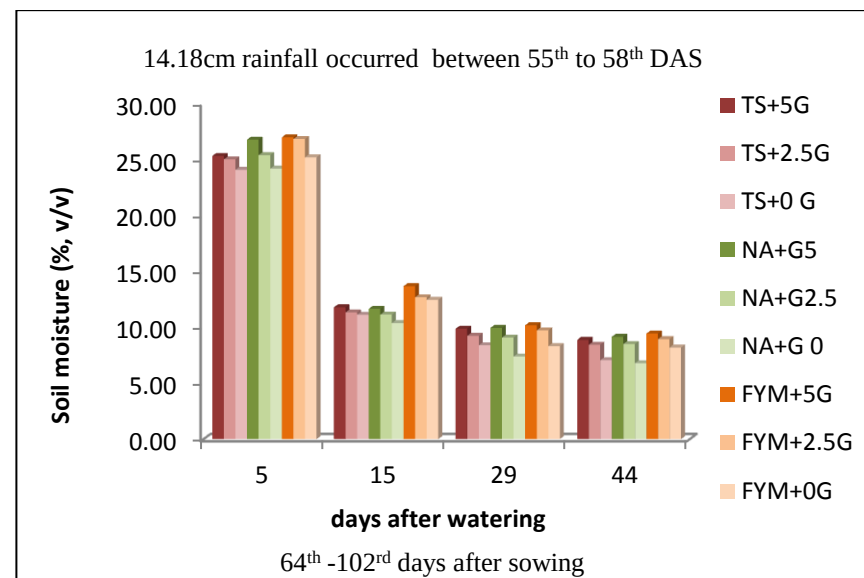
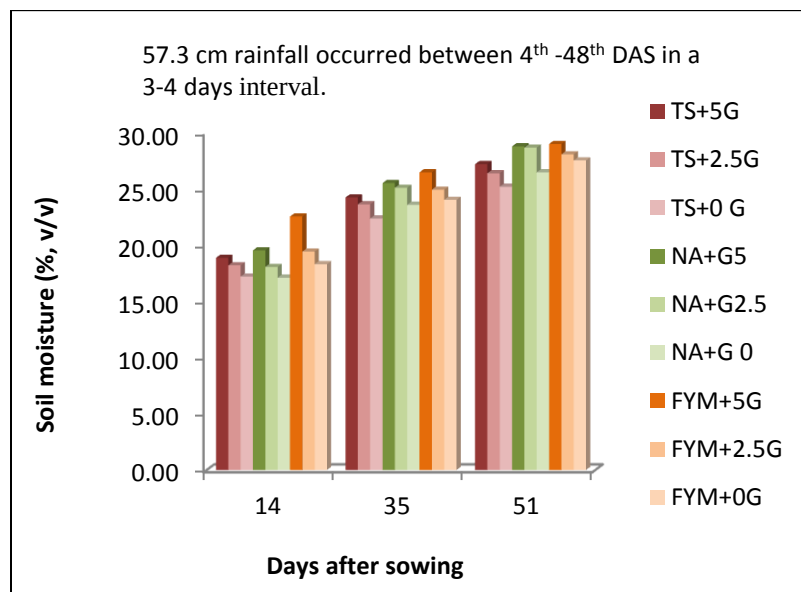


Fig. 4.2.2b. Soil moisture content (upto 15 cm soil layer) of different amendments under varying rates of hydrogel application during the *kharif* season (July – October) 2010. (NA: No amendment; TS: Tank soil; FYM: Farmyard manure and G: hydrogel)

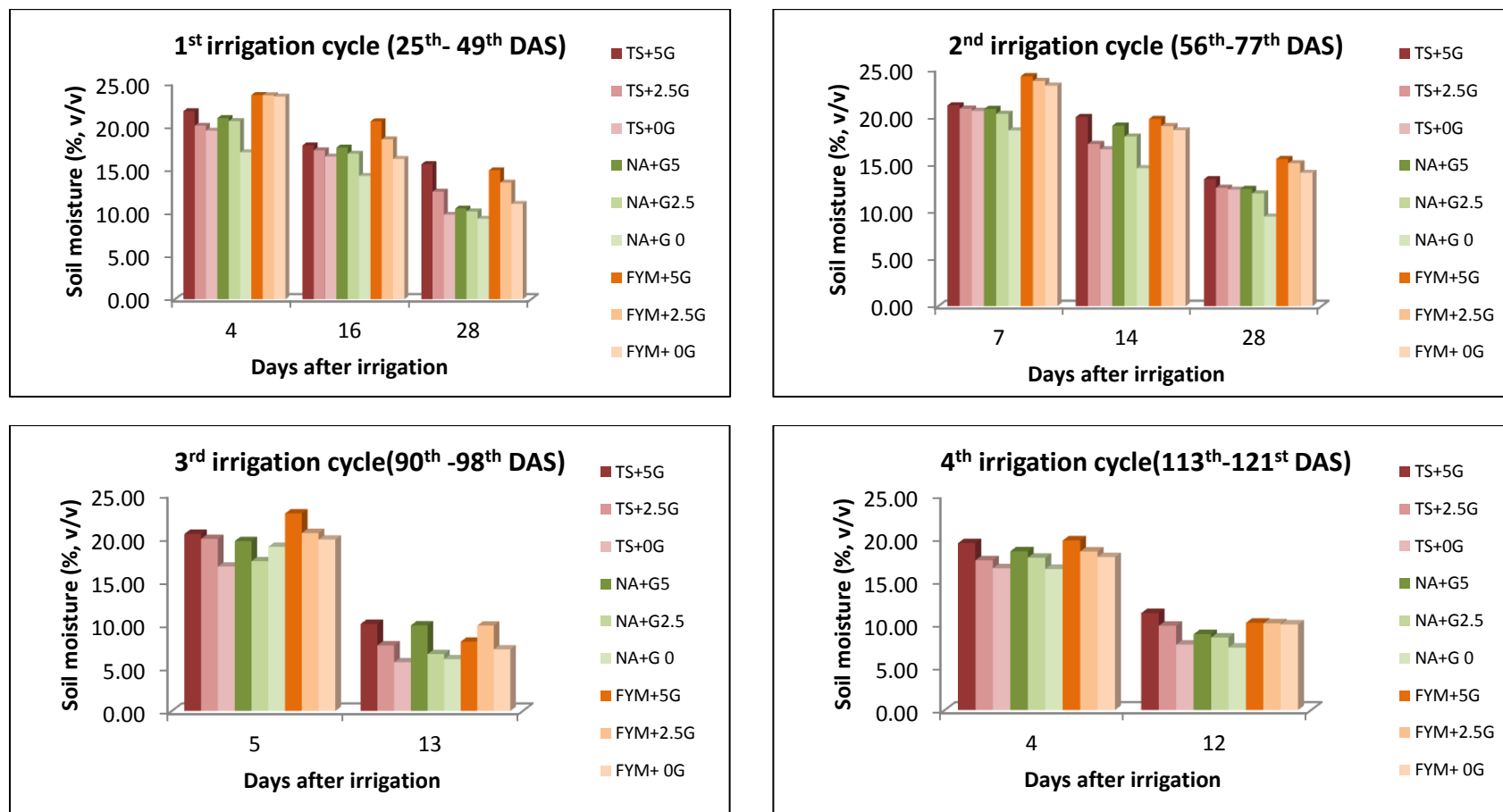


Fig. 4.2.2c. Soil moisture content (upto 15 cm soil layer) of different amendments under varying rates of hydrogel application during the *rabi* season (November – April) 2009-10. (NA: No amendment; TS: Tank soil; FYM: Farmyard manure and G: hydrogel)

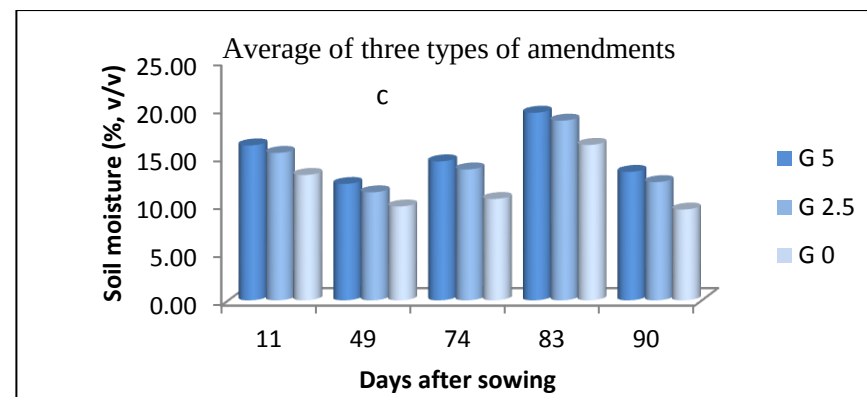
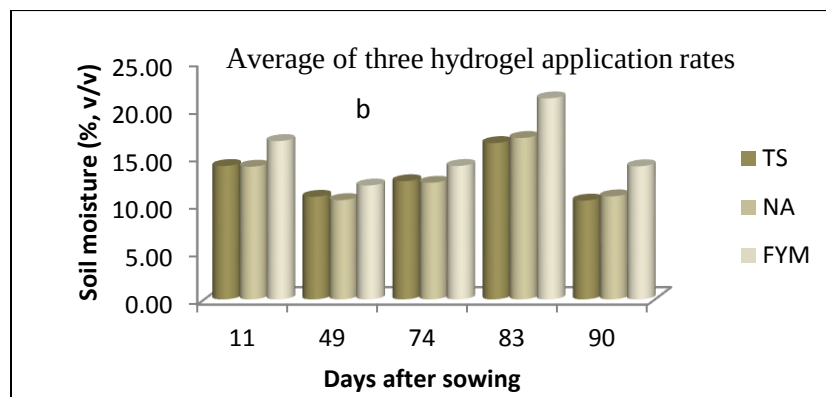
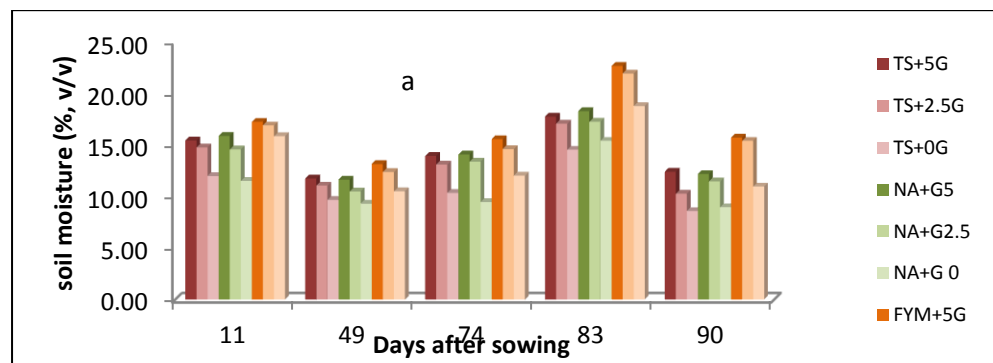


Fig. 4.3.1a. (a) Soil moisture content (up to 15 cm soil layer) of different amendments under varying rates of hydrogel application during the *kharif* season (July-October) 2009; (b) Soil moisture content (up to 15 cm soil layer) under different amendments (average of three hydrogel rates); (c) Soil moisture content (up to 15 cm soil layer) under different hydrogel application rates (average of three amendment types);(NA: No amendment; TS: Tank soil; FYM: Farmyard manure and G: hydrogel)

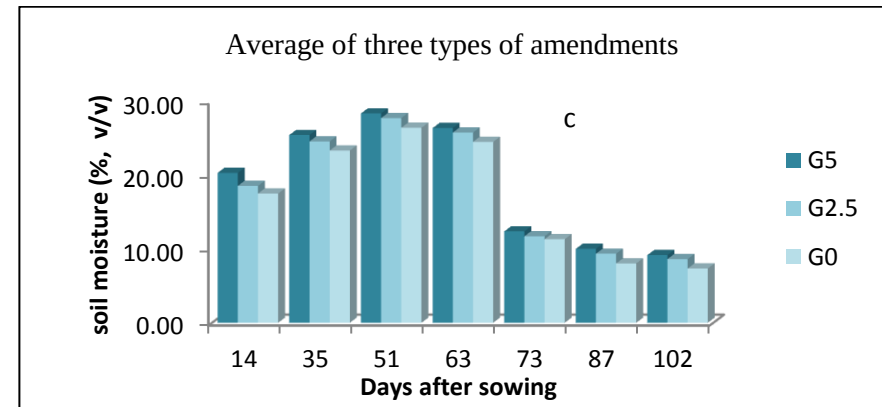
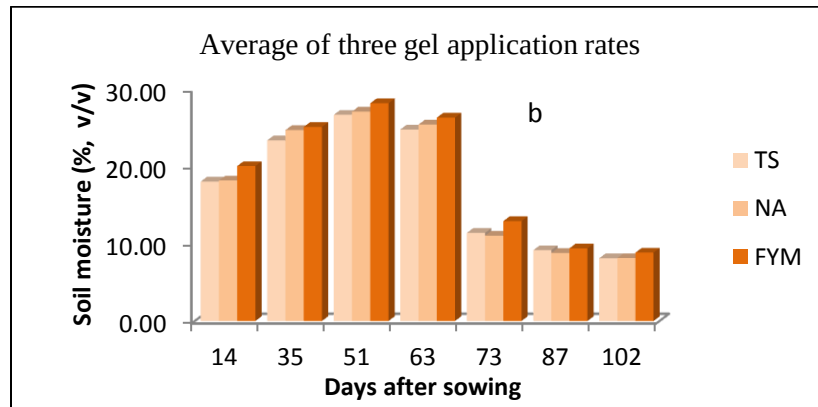
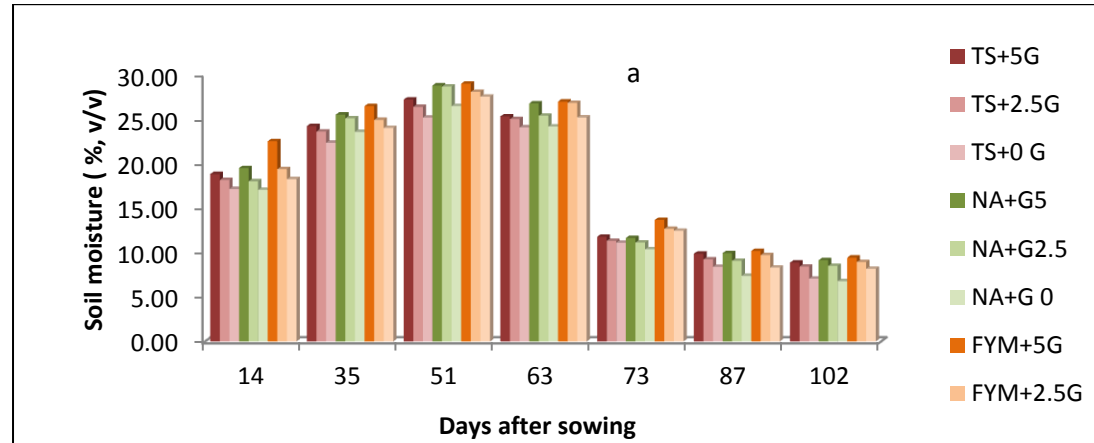


Fig. 4.3.1b. (a) Soil moisture content (up to 15 cm soil layer) of different amendments under varying rates of hydrogel application during the *kharif* season (July-October) 2010; (b) Soil moisture content (up to 15 cm soil layer) under different amendments (average of three hydrogel rates); (c) Soil moisture content (up to 15 cm soil layer) under different hydrogel application rates (average of three amendment types); (NA: No amendment; TS: Tank soil; FYM: Farmyard manure and G: hydrogel)

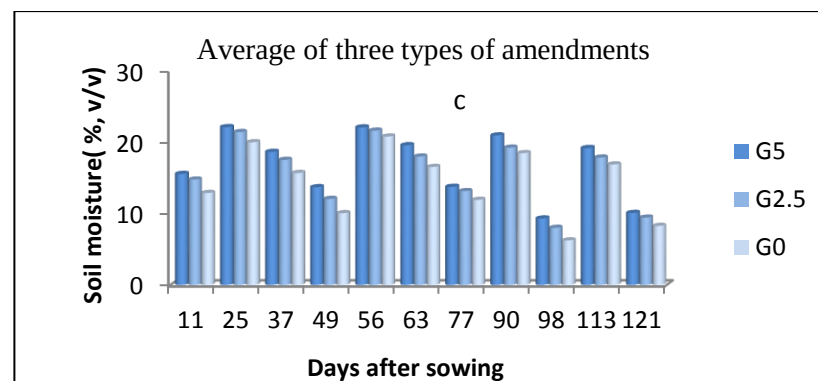
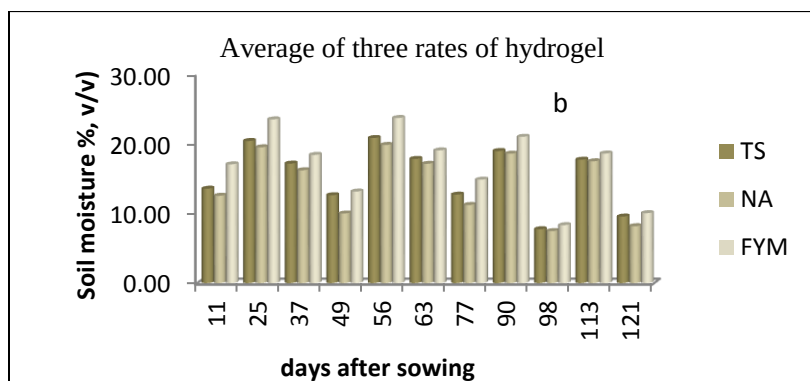
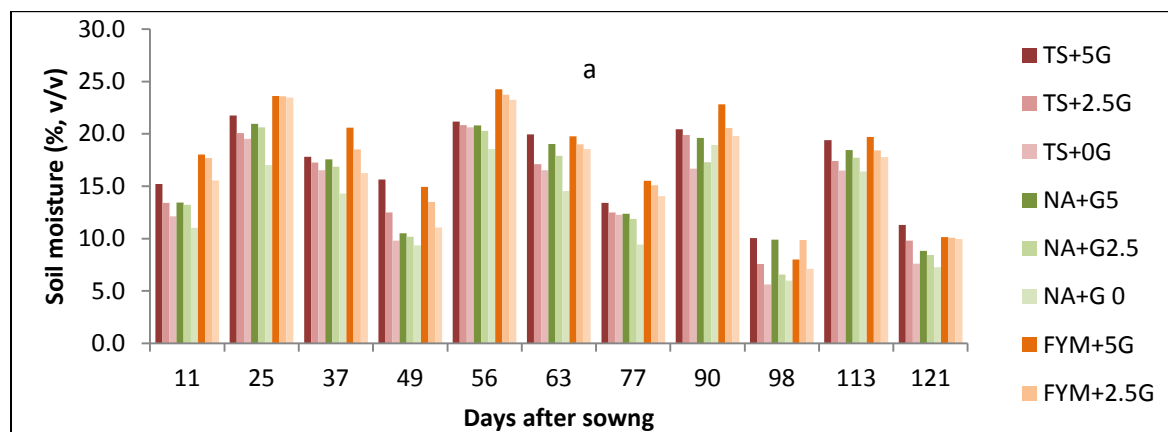


Fig.4.3.1c. (a) Soil moisture content (up to 15 cm soil layer) of different amendments under varying rates of hydrogel application during the *rabi* season (November-April) 2009-10; (b) Soil moisture content (up to 15 cm soil layer) under different amendments (average of three hydrogel rates); (c) Soil moisture content (up to 15 cm soil layer) under different hydrogel application rates (average of three amendment types); (NA: No amendment; TS: Tank soil; FYM: Farmyard manure and G: hydrogel)

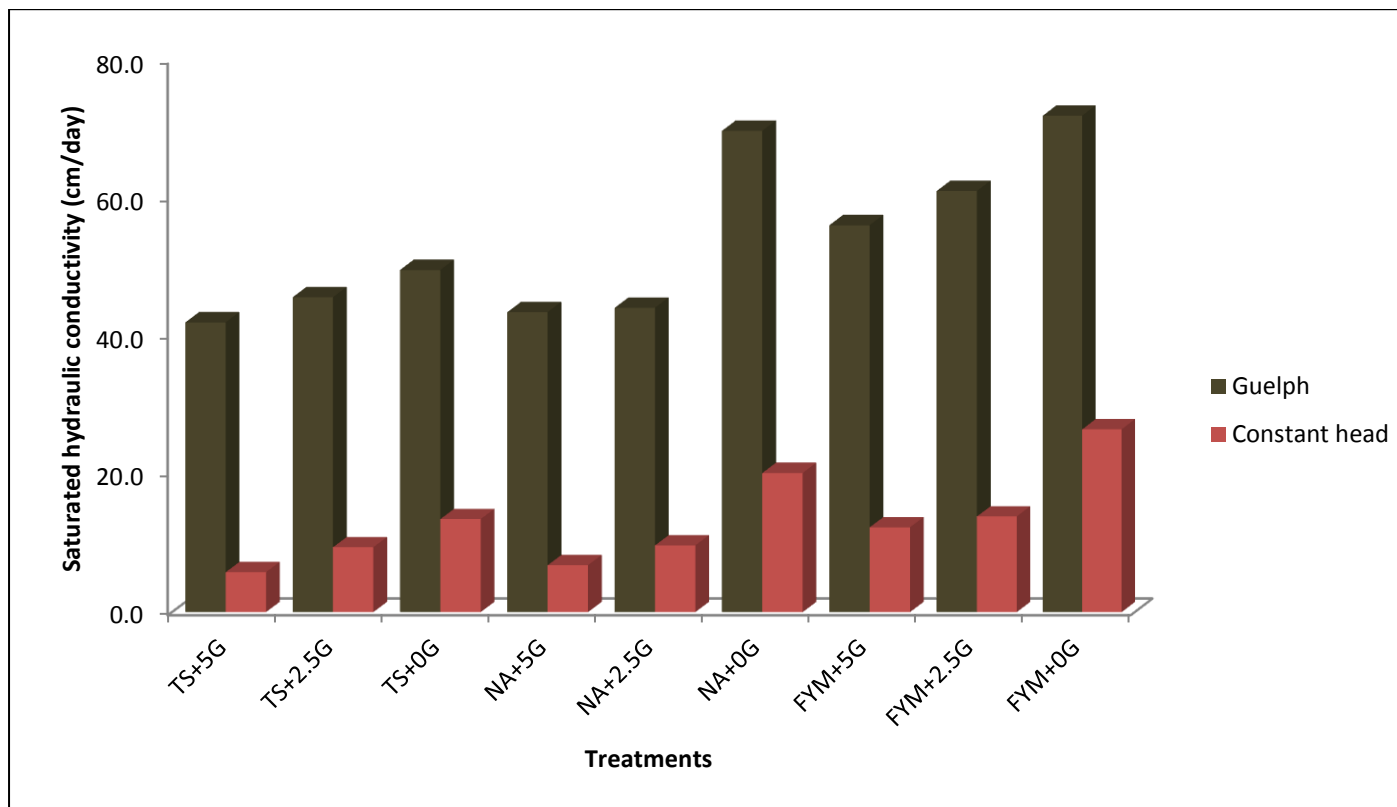


Fig. 4.3.2. Comparison of K_s measured by Guelph Permeameter (in situ) and Constant head method (in laboratory) during *rabi* season 2009-10; (NA: No amendment; TS: Tank soil; FYM: Farmyard manure and G: hydrogel)

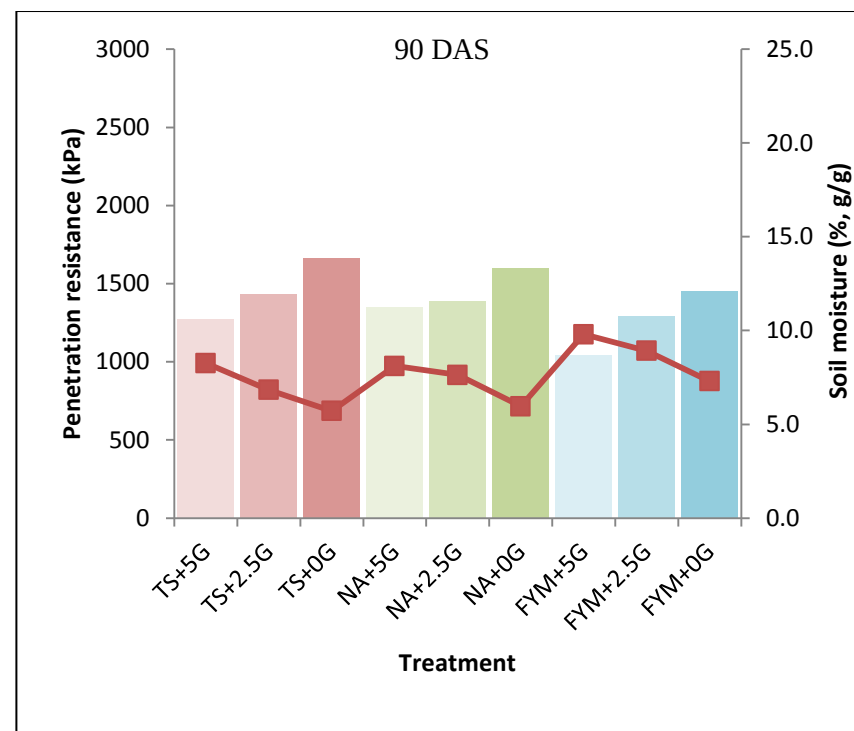
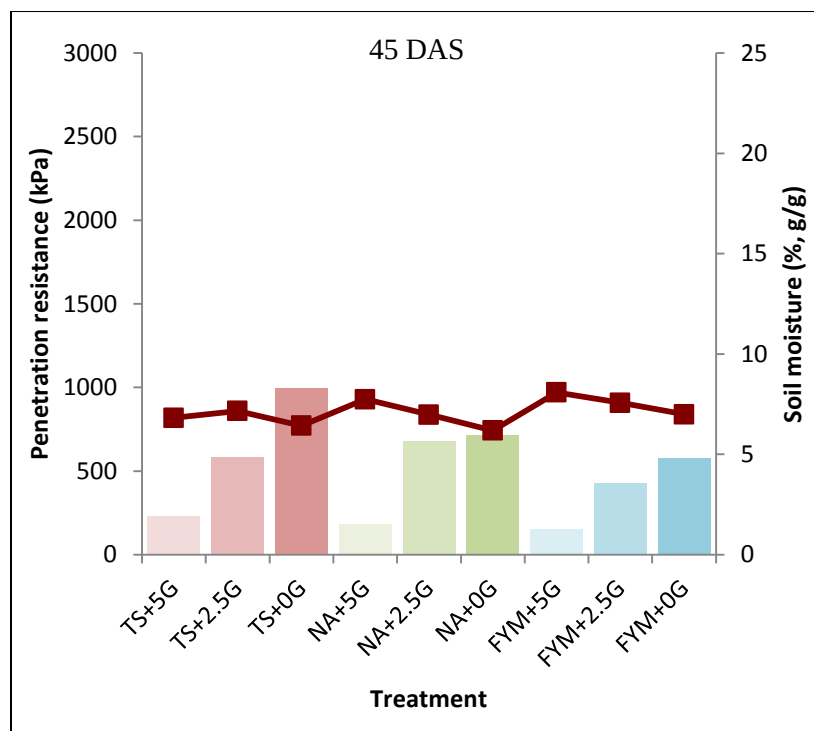


Fig. 4.3.3a. Soil Penetration resistance (0-10cm) of different amendments under varying rates of hydrogel application during the *kharif* season (July – October 1) 2009; (NA: No amendment; TS: Tank soil; FYM: Farmyard manure and G: hydrogel)

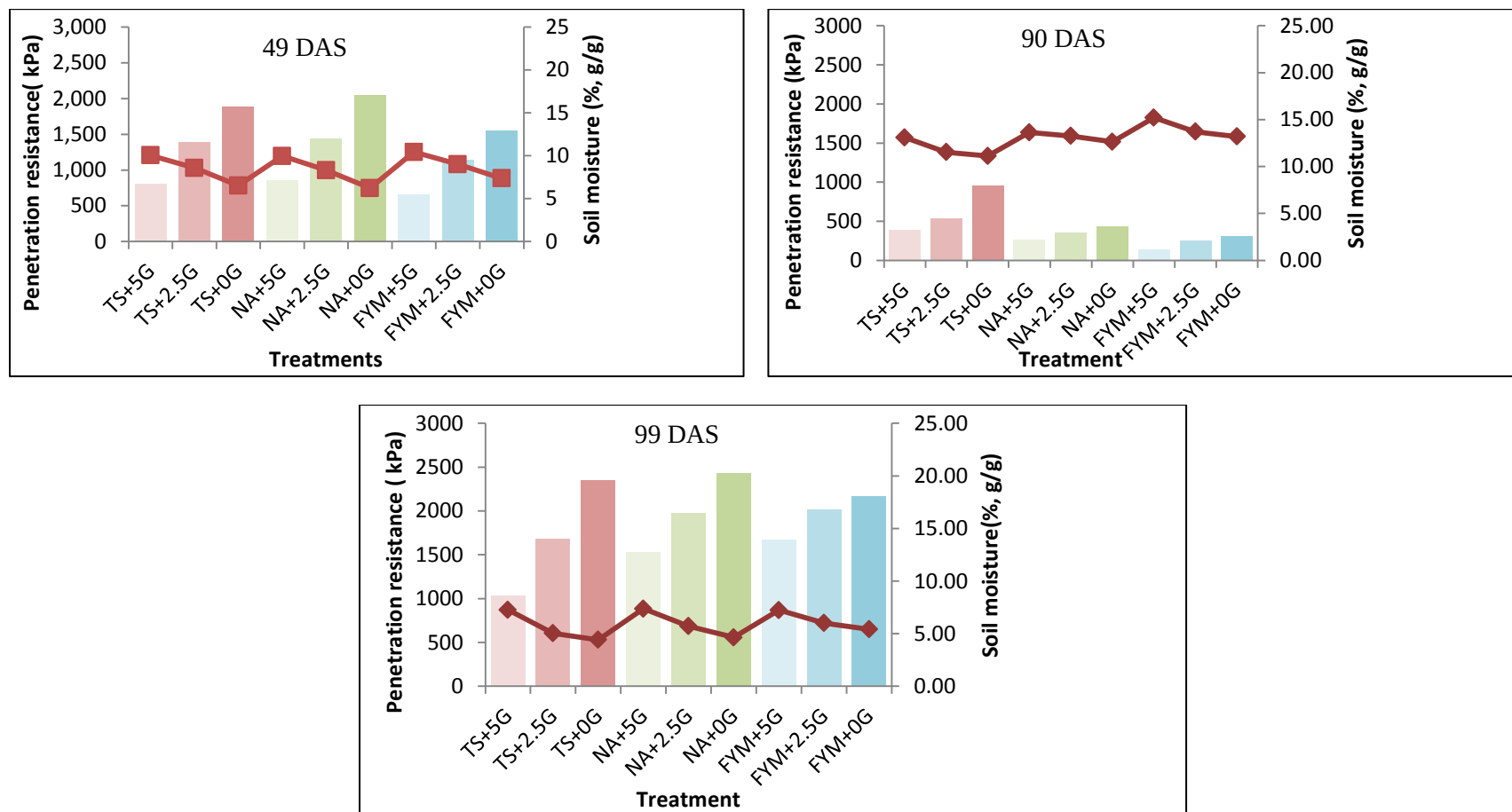


Fig. 4.3.3b. . Soil Penetration resistance (0-10cm) of different amendments under varying rates of hydrogel application during the *rabi* season (November - April) 2009-10; (NA: No amendment; TS: Tank soil; FYM: Farmyard manure and G: hydrogel)

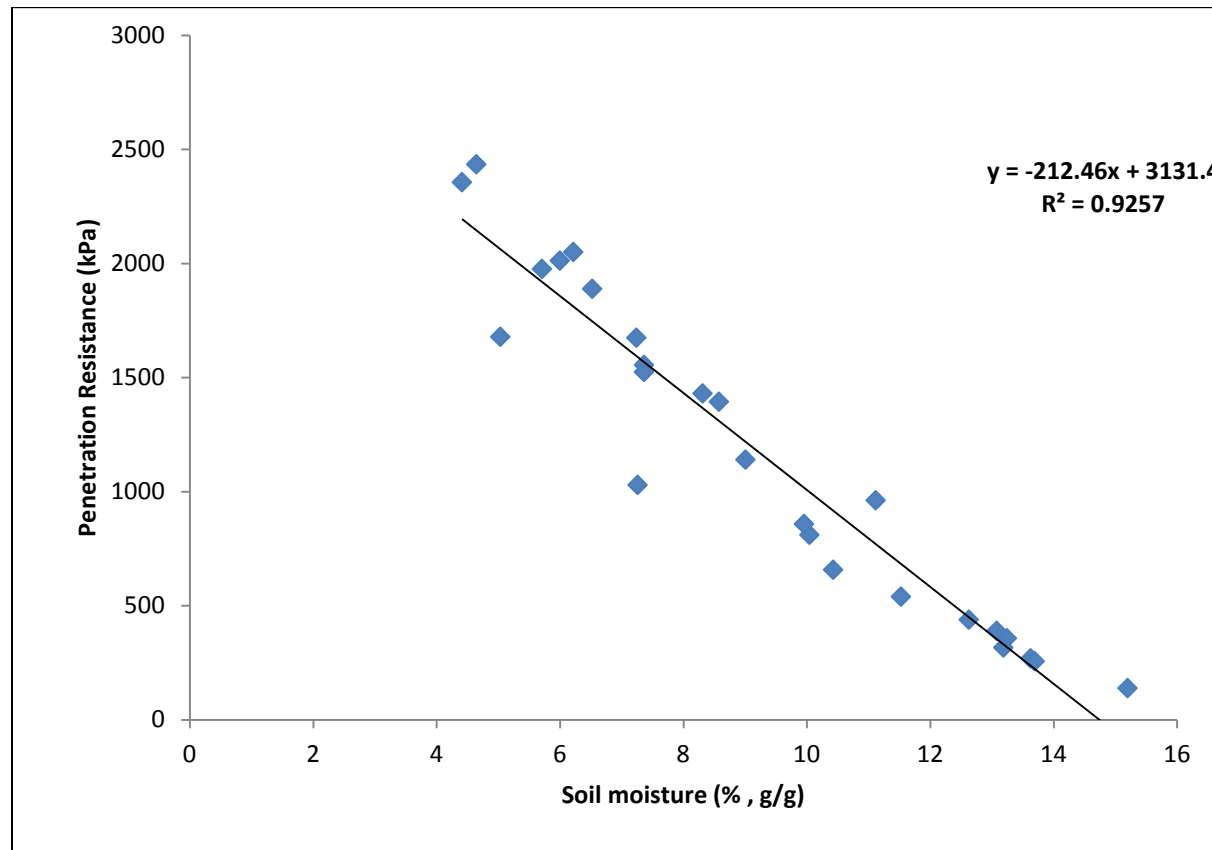


Fig. 4.3.4. Relationship between penetration resistance and soil moisture during *rabi* season (November-April) 2009-10.

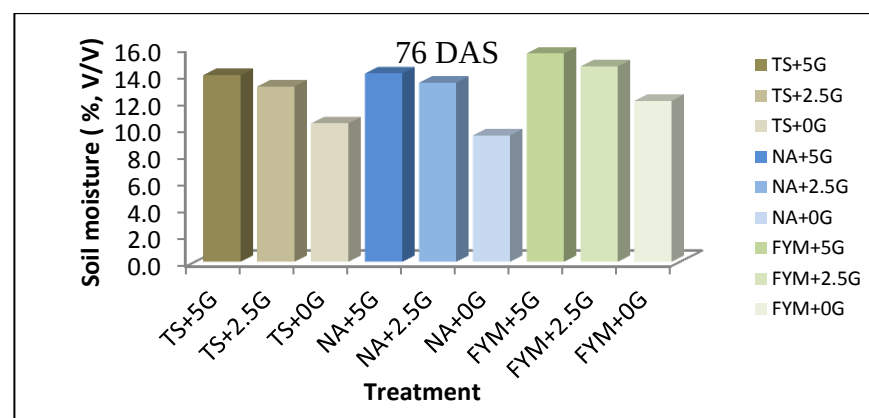
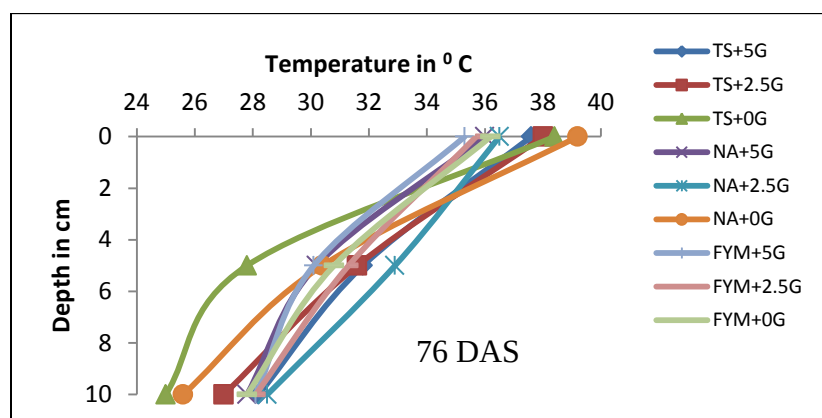
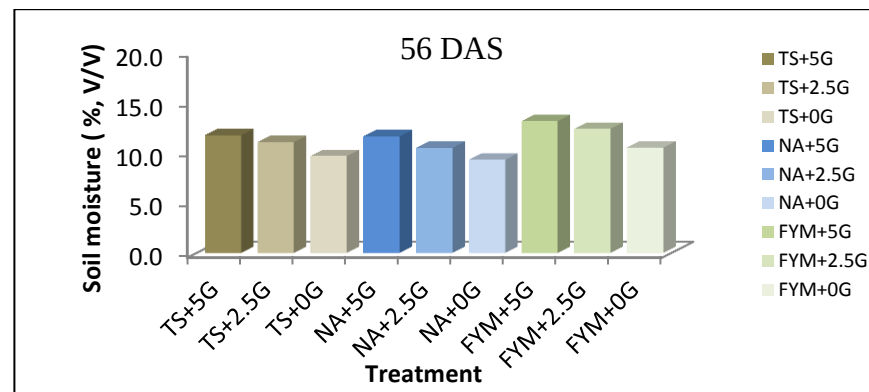
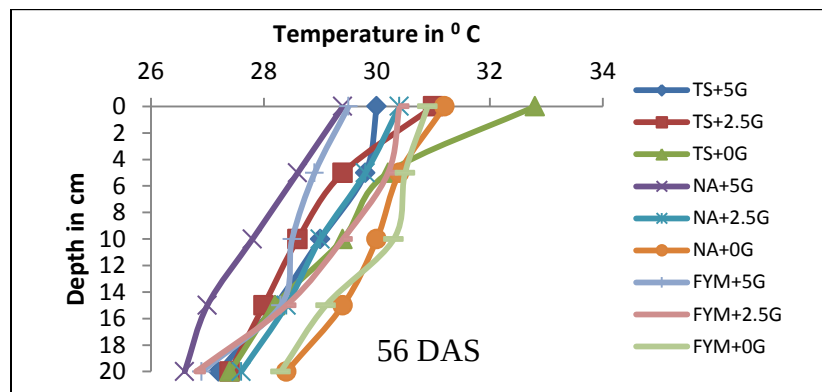


Fig. 4.3.5a. Soil temperature and soil moisture content (upto 15 cm soil layer) of different amendments under varying rates of hydrogel application during the *kharif* season (July-October) 2009; (NA: No amendment; TS: Tank soil, FYM: Farmyard manure and G: hydrogel)

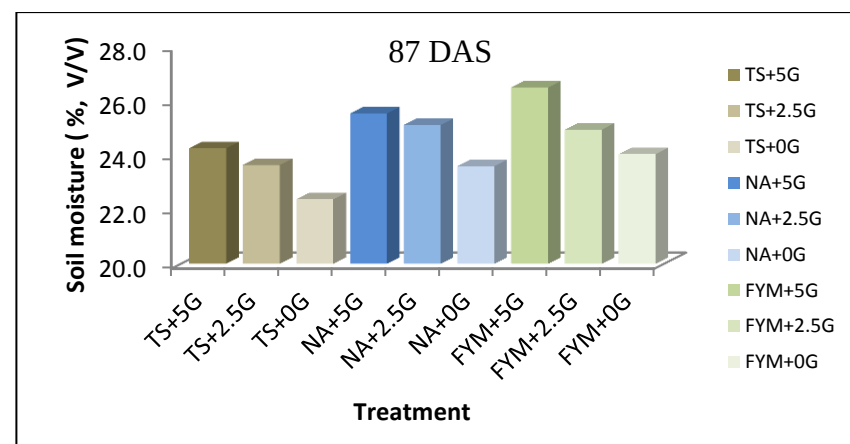
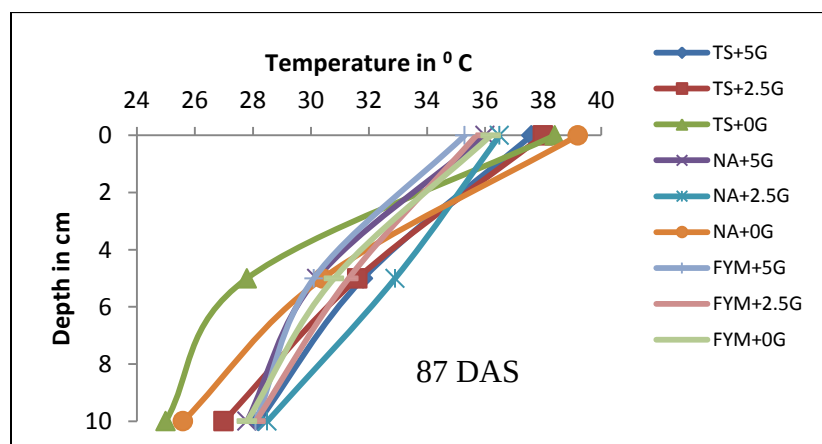
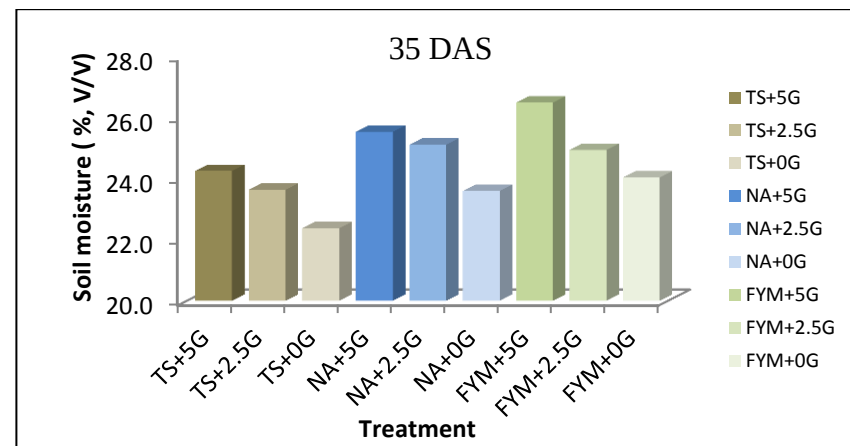
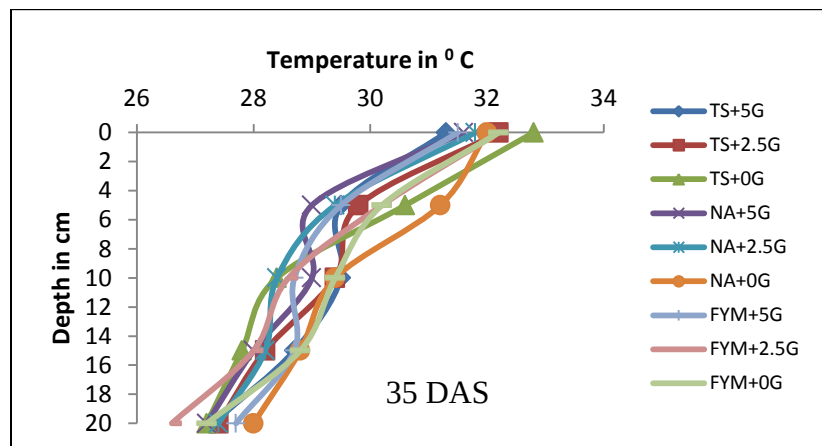


Fig. 4.3.5b. Soil temperature and soil moisture content (upto 15 cm soil layer) of different amendments under varying rates of hydrogel application during the *kharif* season (July-October) 2010; (NA: No amendment; TS: Tank soil; FYM: Farmyard manure and G: hydrogel)

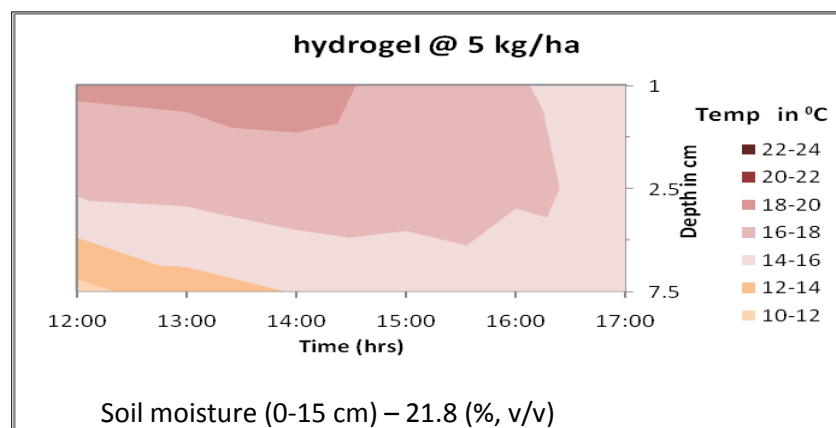
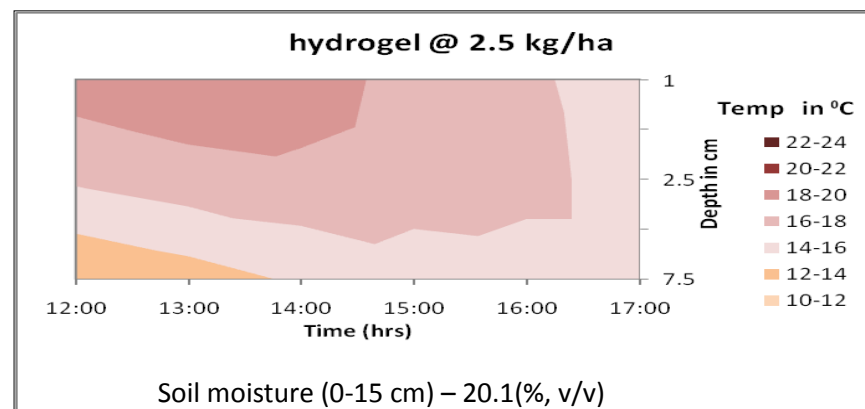
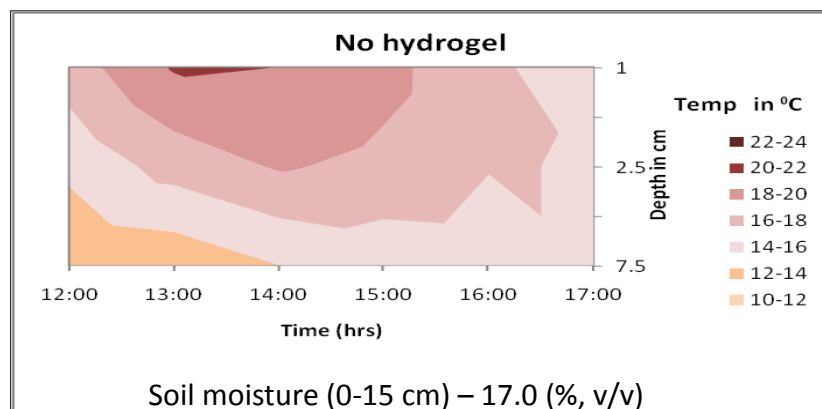


Fig. 4.3.5c1. Hourly variation of temperature during day time on 25th DAS [wet SWC conditions (5 DAI)] under different rates of hydrogel application during *rabi* season (November-April) 2009 -10.

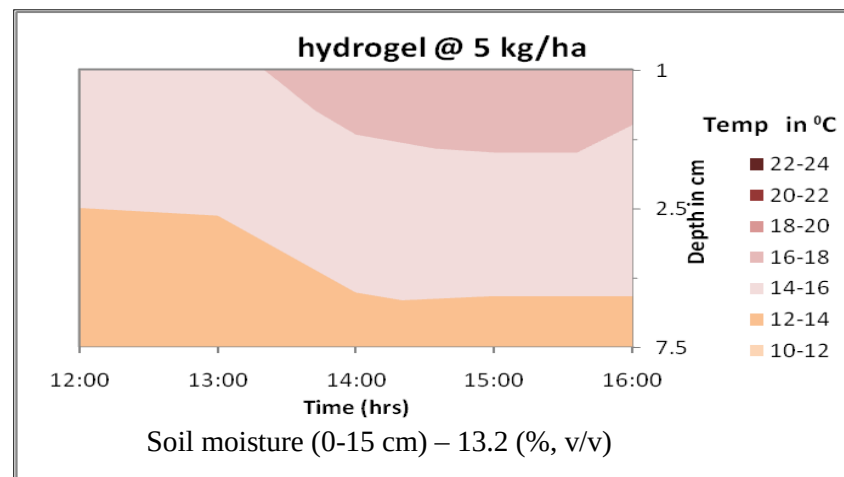
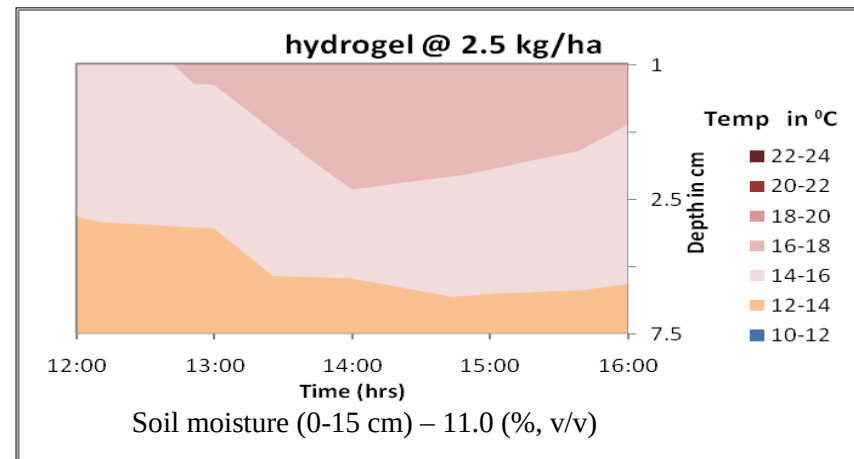
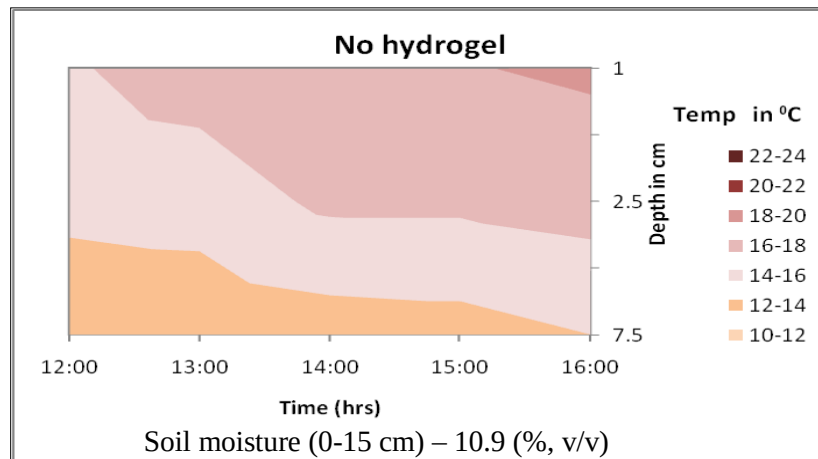


Fig. 4.3.5c2. Hourly variation of temperature during day time on 49th DAS [wet SWC conditions (5 DAI)] under different rates of hydrogel application during *rabi* season (November-April) 2009 -10.

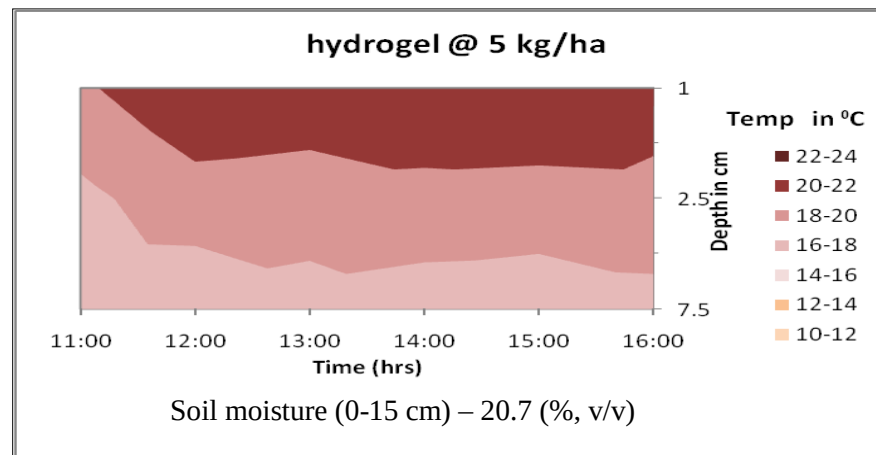
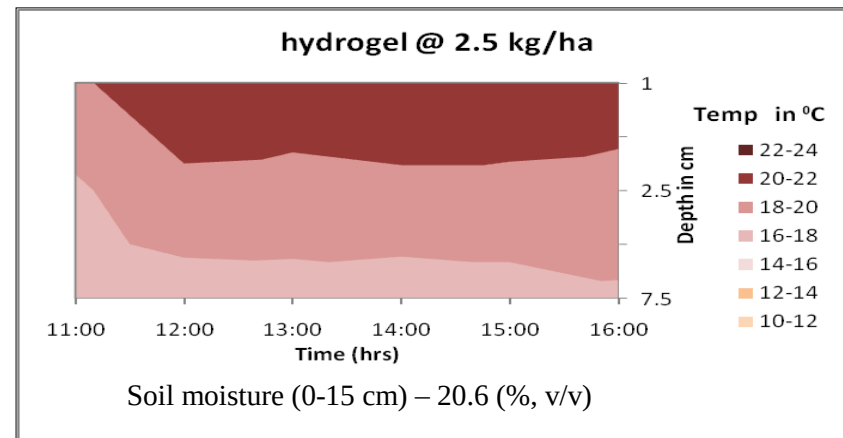
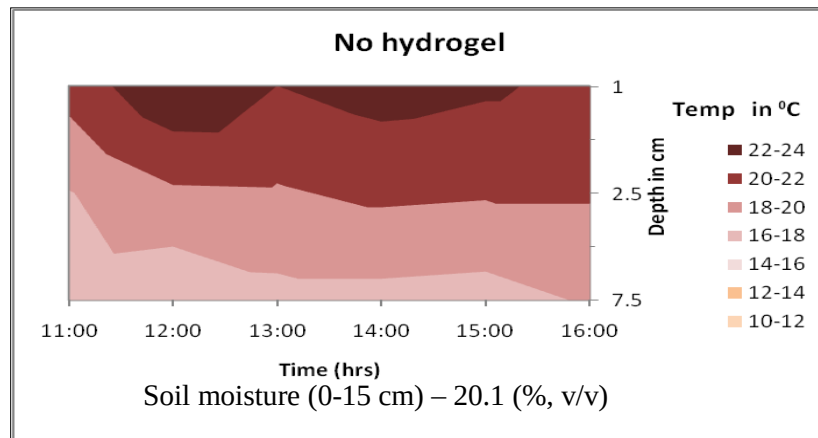


Fig. 4.3.5c3. Hourly variation of temperature during day time on 90th DAS [wet SWC conditions (5 DAI)] under different rates of hydrogel application during *rabi* season (November-April) 2009 -10.

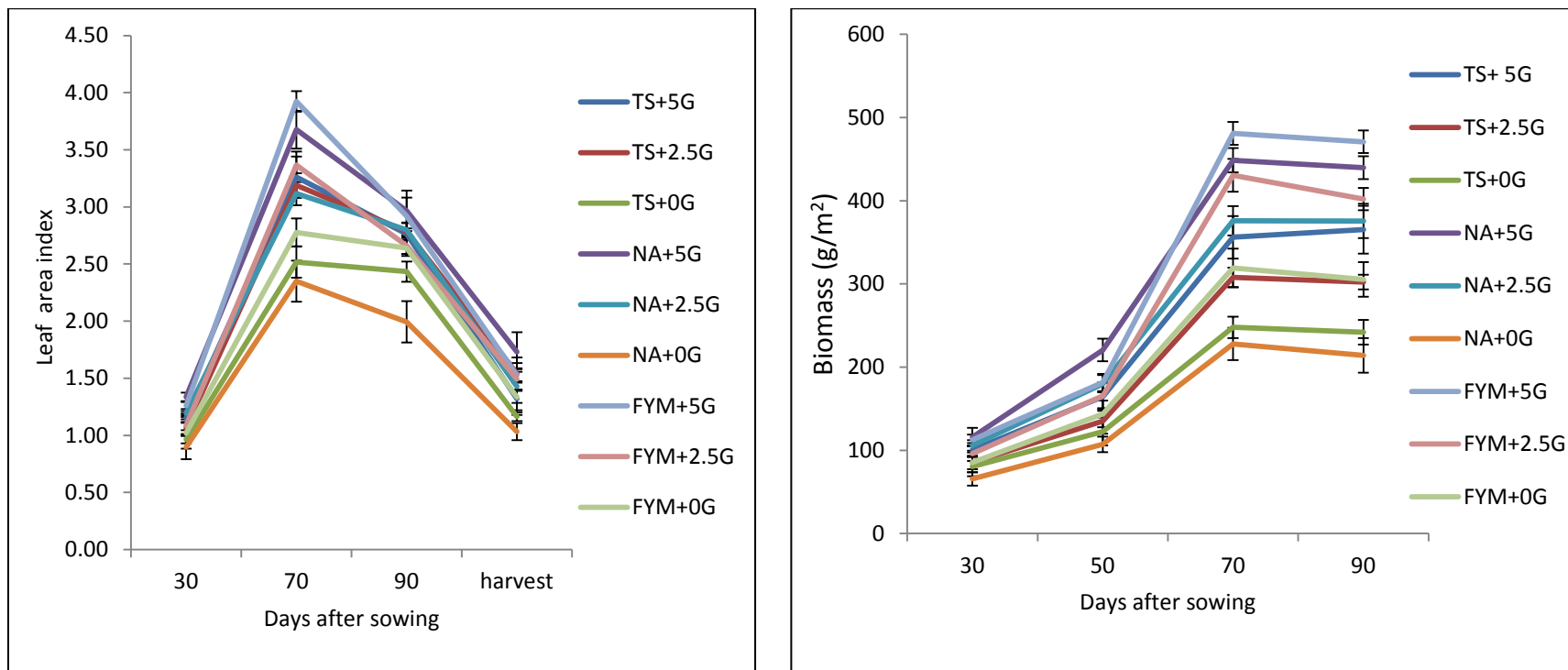


Fig. 4.4.1a. Leaf area index (m^2m^{-2}) and dry biomass (g m^{-2}) of soybean as influenced by gel application rates and soil amendment type during 2009; (NA: No amendment; TS: Tank soil; FYM: Farmyard manure and G: hydrogel)

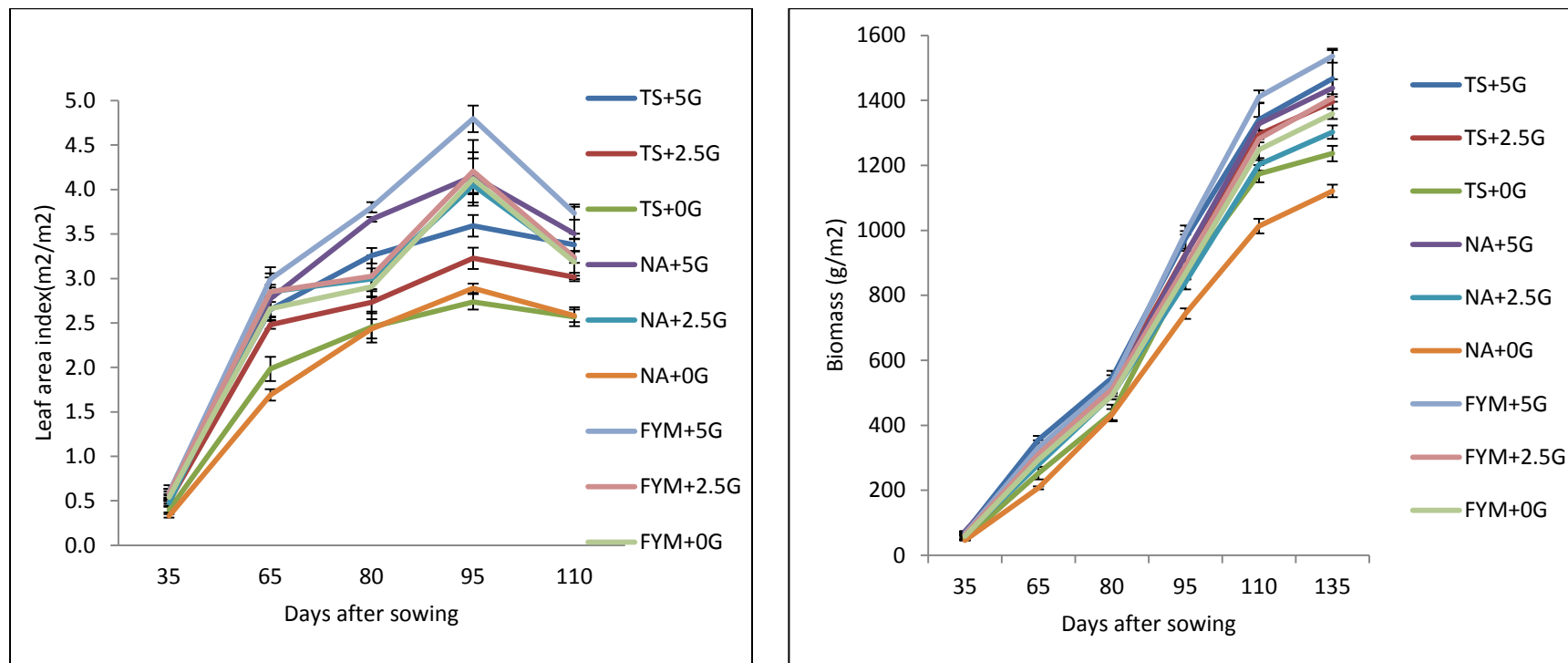


Fig. 4.4.1b. Leaf area index (m^2m^{-2}) and dry biomass (g m^{-2}) of wheat as influenced by gel application rates and soil amendment type during 2009-10; (NA: No amendment; TS: Tank soil; FYM: Farmyard manure and G: hydrogel)

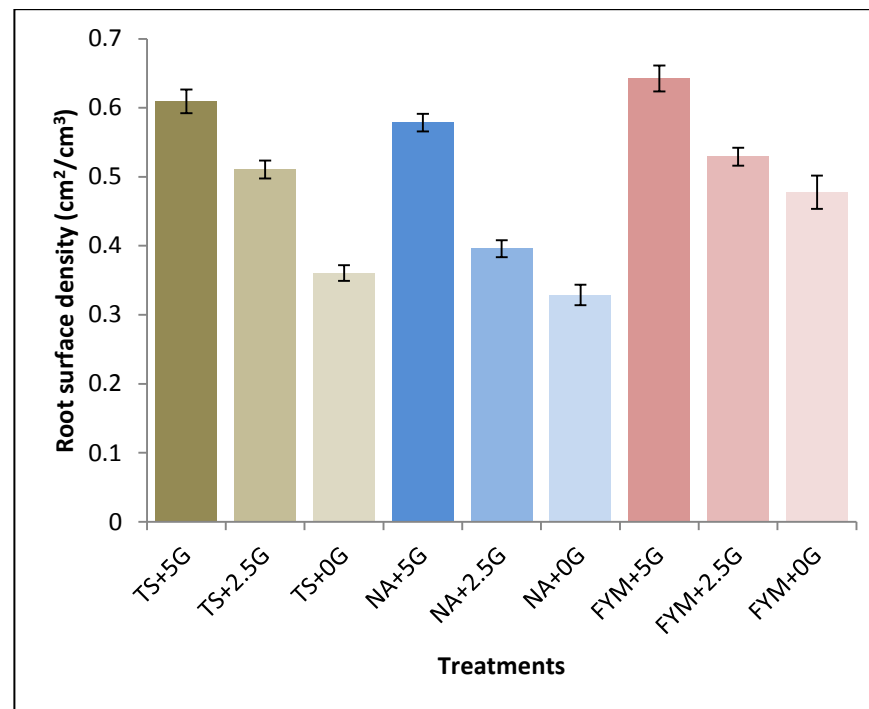
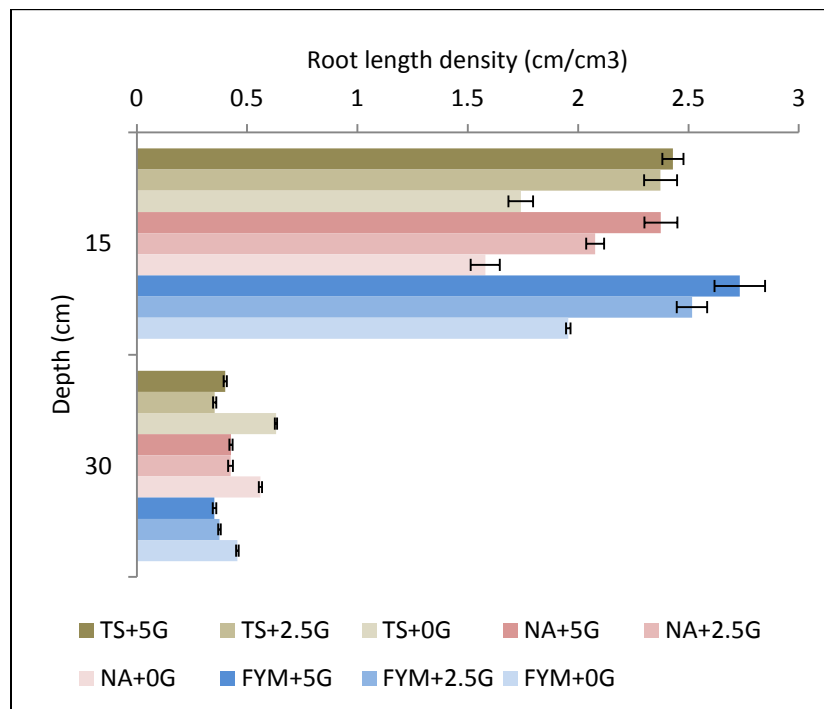


Fig. 4.4.2a. Root length density(cm cm⁻³) and root surface density (cm²cm⁻³) of soybean as influenced by gel application rates and soil amendment type during 2009, (NA: No amendment; TS: Tank soil; FYM: Farmyard manure and G: hydrogel)

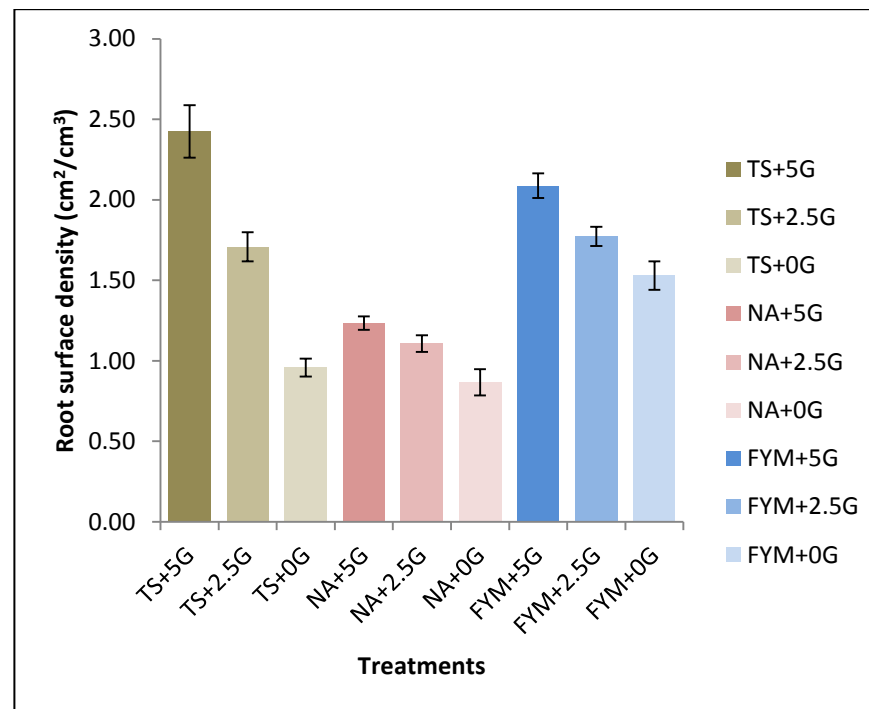
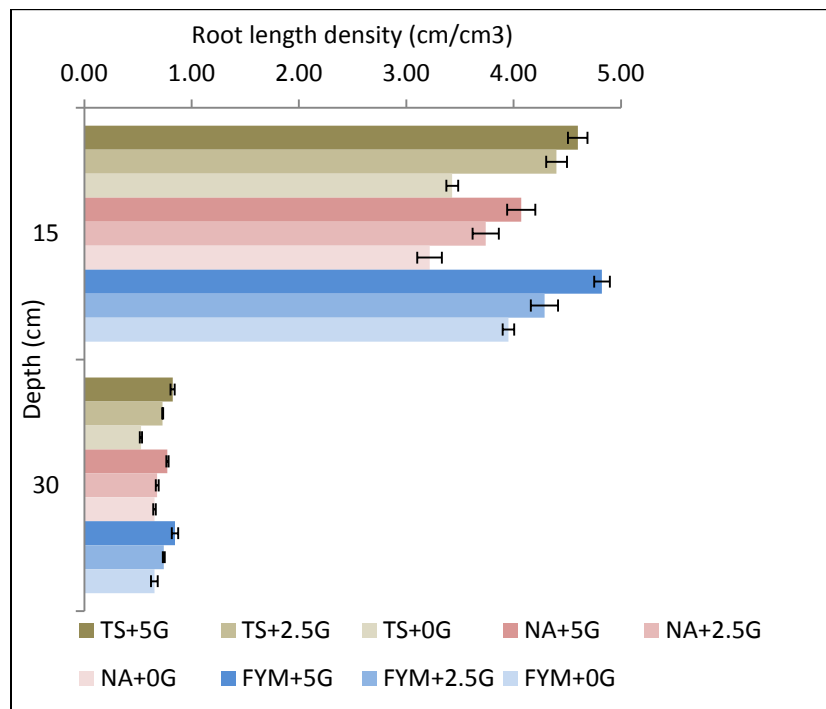


Fig. 4.4.2b. Root length density(cm cm⁻³) and root surface density (cm²cm⁻³) of wheat as influenced by gel application rates and soil amendment type during 2009-10, (NA: No amendment; TS: Tank soil; FYM: Farmyard manure and G: hydrogel)

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APPENDIX-I


Mean weekly weather data during *kharif*, 2009.

Week no.	Max. T. (°C)	Min. T. (°C)	Rain fall (mm)	RH(M) %	RH (E) %	Pan evaporation (mm)
28	37.7	27.4	2.4	77	50	8.3
29	35.5	27.2	1.0	79	63	9.6
30	35.7	27.3	8.8	74	71	7.2
31	35.1	26.3	101.6	76	57	6.2
32	36.9	27.7	7.8	62	48	7.7
33	36.5	27.2	19.8	74	61	7.0
34	32.9	24.6	65.0	84	61	4.4
35	33.3	25.0	42.2	87	74	4.7
36	32.9	24.6	120.4	90	73	3.6
37	30.6	22.7	119.3	93	73	3.7
38	32.2	21.8	1.0	91	52	3.7
39	36.4	24.5	0.0	81	46	6.2
40	35.6	23.6	0.0	82	43	5.8
41	32.2	19.7	0.3	88	48	3.5
42	33.9	16.9	0.0	90	28	3.8
43	32.4	13.8	0.0	86	29	5.5
44	31.0	11.8	0.0	78	39	5.0

APPENDIX-II**Mean weekly weather data during *kharif*, 2010**

Week no.	Max. T. (°C)	Min. T. (°C)	Rain fall (mm)	RH(M) %	RH (E) %	Pan evaporation (mm)
29	33.3	26.3	47.2	89	71	4.6
30	32.5	26.1	34.8	86	81	4.4
31	32.2	26.5	12.0	90	71	4.0
32	34.1	25.7	106.4	89	72	5.2
33	31.2	25.7	129.0	95	86	3.3
34	31.8	24.8	71.2	95	74	2.8
35	33.3	25.3	43.4	94	75	5.2
36	31.2	25.0	76.2	95	84	3.6
37	30.5	23.7	52.8	95	80	3.3
38	28.3	22.4	141.8	97	77	2.6
39	33.0	21.4	0.0	91	53	5.0
40	33.1	20.3	0.0	92	54	4.1
41	33.8	19.5	0.0	85	46	4.7
42	31.7	19.8	22.0	85	51	3.6
43	29.0	14.2	0.0	86	37	3.6
44	29.0	13.4	0.0	93	37	3.4
45	28.4	14.8	3.6	93	46	2.9
46	26.0	14.7	9.0	92	57	2.5

APPENDIX-III**Mean weekly weather data during *rabi*, 2009-10**

Week no.	Max. T. (°C)	Min. T. (°C)	Rain fall (mm)	RH(M) %	RH (E) %	Pan evaporation (mm)
48	25.8	7.2	0	92	44	2.1
49	22.2	8.0	0	92	51	1.8
50	23.9	6.7	0	93	45	2.0
51	22.7	7.5	1	88	43	1.7
52	21.2	3.9	0	91	33	2.3
1	19.3	4.2	0	92	54	2.1
2	15.2	6.9	0	92	73	1.4
3	15.0	6.0	0	93	68	1.4
4	17.6	5.8	0	93	57	1.5
5	23.8	8.4	0	94	50	2.2
6	23.4	7.0	0	91	34	2.8
7	23.6	11.1	11.8	91	56	1.7
8	22.7	7.4	0	90	39	2.3
9	27.7	12.8	1.2	89	38	3.9
10	31.2	15.4	0	82	31	5.9
11	28.9	12.5	0	85	31	5.6
12	33.4	14.7	0	88	30	6.8
13	37.9	17.6	0	78	20	7.0
14	37.7	18.1	0	71	19	7.8
15	39.2	19.6	0	44	14	8.7
16	42.2	22.3	0	49	28	10.2
17	40.9	24.4	0	57	34	9.6