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Role of Physics in Agriculture[1]

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Owing to the great advances in agricultural chemistry in the 19th century, little work was done during that period in soil physics. Agriculture was slowly recognised on an industrial basis to supply the markets of the new manufacturing centres. The credit for the first systematic study of the physical properties of soil belongs to Schubler who worked in the early 19th century. In Germany Prof. Wollny initiated the subject Agricultural Physics and a journal of Agricultural Physics was published regularly from 1878 to 1898. This was a journal that had unique distinction of being the only one devoted exclusively to Agricultural Physics.

Soil is a three-phase system with solids, liquid and air. Almost all the nutrients required by the plants are in soil solution and hence water affects intensely many physical and chemical reactions of the soil as well as the plant growth. Water molecule is peculiar in its own sense. It is essentially spheroidal. The hydrogen ions are only partially neutralised by the negative valencies of the oxygen ions and hence it behaves like a di-pole molecule. Water rises in capillary tubes due to surface tension. (Capilla in Latin means hair).

Rocks disintegrate into smaller and smaller sizes due to the impact of the atmosphere, penetrating roots and biological activity. The disintegrated particles are gravel, sand, silt and clay. In the international system of classification particles of the sizes given below are recorded in mechanical analysis.

Up to the silt stage all the particles are the chips of the old rock, but at the finest stage of the silt the particles interact chemically and like a butterfly coming out of cocoon the clay emerges as a beautiful crystal from the porous silt particle.

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Table 1. Classification of soil particles

Soil particle	Diameter in mm
Coarse sand	2 - 0.2
Fine Sand	0.2 - 0.02
Silt	0.02 - 0.002
Clay	< 0.002

Sieves are used for separating the coarse particles. The smaller particles which are of great importance in determining soil properties are accounted for by the famous Stokes' Law given by

$$v = \frac{2}{9} g r^2 \left(\frac{\sigma - \rho}{\eta} \right) \qquad \text{.................(1)}$$

where v = rate of fall; g = acceleration due to gravity; r = radius of the spherical particle; ρ = density of the liquid; σ = density of particle and η = viscosity of the liquid.

A. Basic Studies on Clays and Soil-Water Interaction

1. Clays

Clays are negatively charged particles, platy in structure and have a large surface area as compared to the rest of the particles. In fact, a fine bentonite clay has a surface area of 800 square meters per gram. It is around these negatively charged clay particles the cations, that form the plant food, exist. This property is expressed as milli-equivalents of cations per 100 gram of dry clay and is called the Cation Exchange Capacity (CEC). For poorly charged kaolinite clay it works out to be round about 5 milli-equivalents while for montmorillonite (bentonite clay) it is around 100 milli-equivalents. The potential fertility status of the soil is a function of the type of clay present in it.

1.1 Helmholtz's Double Layer : The classical concept of an electric double layer around a charged particle suspended in water or in a solution was introduced by Helmholtz (1879). This view was modified by Guoy (1916) and Chapman (1913) by introducing a diffuse double layer. The potential difference across the diffuse layer is commonly regarded as electrokinetic potential. The distribution of anions and cations between any two flat charged surfaces can be regularly visualised as below:

When the two negatively charged parallel plates (Fig. 1) are pressed together, the ionic concentration that is thrown out would contain excess of anions than cations. This principle is used in desalinisation process and, therefore, would not represent the concentration in equilibrium with the soil particles that is soil solution.

1.2 Negative Adsorption and Calculation of the Surface Area of Bentonite Clay : Schofield (1947) showed that the surface of the negatively charged clay bentonite could be measured by negative adsorption measurements. He obtained for the general case, where all the extracted ions have a valency υ and all the repelled ions have valency $\frac{\upsilon}{P}$ the equation

$$\frac{\Gamma-}{n} = \frac{q}{\sqrt{\upsilon\beta.n}} - \frac{4}{\upsilon\beta.\Gamma} \quad \text{.....................(2)}$$

which is sufficiently accurate in practice provided that the second term is less than one fifth of the first. $\Gamma-$ is the negative adsorption of the propelled ion per unit area (milli-equivalents/ cm^2) and n the normality of the external solution (milli-equivalents/cm^2), q is a factor, which depends on the valency ratio Γ and β principally depends on the dielectric constant. The results of the experimental determinations are conveniently expressed by the quantity "V" obtained by dividing the negative adsorption expressed in milli equivalents per 100 g of sorbate by the normality of the solution. When V is plotted against $\frac{q}{\sqrt{\upsilon \cdot \beta \cdot n}}$, a straight line will be obtained between certain limits of concentration if the necessary conditions are fulfilled, its slope giving the surface area per 100 g of sorbate. Schofield predicted that 100 g of pure montmorillonite (density 2.5) when completely dispersed should have a surface area of 8.0 x 10^8 cm^2 assuming the plates to be 10 A° thick. Mattson's measurements with sodium bentonite, as shown by Schofield, gave a surface area of 4.7 x 10^8 cm^2 per 100 g.

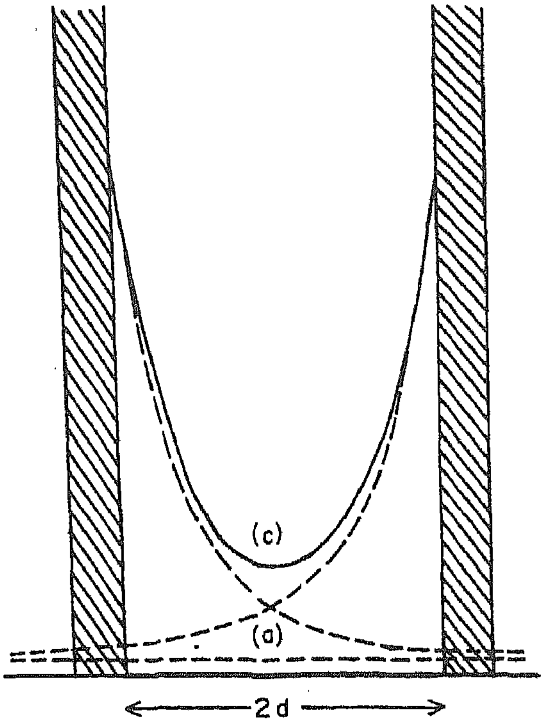

Fig. 1. The distribution of ions in the Gouy layer between two parallel plane micelles. Broken lines indicate unimpeded Gouy layer

The bentonite used by the author (1948) was the finest fraction obtained in a super centrifuge. It was left suspended in water for about a couple of years and completely dispersed. It was, therefore, more suitable for negative adsorption measurements. Moreover, the high reduction in diffusion and conductivity caused by the plates in the bentonite should in some way be effective and therefore available for negative adsorption measurements.

When the values of 'V' are plotted against the values of $\frac{q}{\sqrt{\upsilon \cdot \beta \cdot n}}$, the condition for the applicability of Schofield's equation was not fulfilled. However, taking the average slope of all the four points noted, the apparent area works out to be 7.2 x 10^8 cm^2 per 100 g of bentonite. This is much smaller than that which could be obtained by studying sufficiently low concentrations as to satisfy the conditions. In fact, as the plates are minutely divided in the sample used, the edges of the plates also should contribute to the area.

2. Diffusion Coefficient

Soil water moves through a three-phase system (1) as mass flow, (2) as dispersion and (3) as diffusion. As long as the soil is saturated, mass flow and dispersion are the effective modes of movement. Once the mass flow stops and the soil solution is held in micro-pores, diffusion is the only process through which the nutrient ions migrate. The first measurements of the diffusion of electrolytes were made in 1851 by Thomas Graham (1851). The theory was later developed by Adolf Fick (1855). Fick's law was the basis for most of the experimental work carried out earlier by physical chemists. This required a concentration gradient $\frac{dC}{dx}$ and the diffusion takes place from a higher to a lower concentration.

The fundamental treatment of the problem of diffusion was due to Einstein (1905). He dispensed with the idea of a concentration gradient and said that the diffusion essentially being a thermal process would take place even in a single concentration. According to him it is due to the Brownian movement, completely irregular and deduced the rigorous mathematical equation, which eventually is simple in form. According to him

$$D = \frac{\overline{\Delta x^2}}{2\tau}$$

where $\overline{\Delta x^2}$ is the mean square of displacement of an ion along any axes in an interval of time τ. This new concept of diffusion was used by the author to measure the diffusion coefficients of anions and cations separately under a known total ionic concentration in clays and soils. This concept is one of the two fundamental discoveries on which Einstein (1905) got his Nobel Prize in Physics.

Equation for the diffusion coefficient D in terms of the standard deviation σ :

The quantity of the ion q diffused in any given time is given by the equation

$$q = C_B.A.S.\sqrt{\frac{2}{\Pi}} \qquad \text{.........(3)}$$

where S is the standard deviation in time t.

The rate of change of q is given by

$$\frac{dq}{dt} = C_B.A.\sigma.\sqrt{\frac{2}{\Pi}}\cdot\frac{dS}{dt}$$

$$= \frac{C_o.A}{\sqrt{2\Pi}}.\frac{dS}{dt} \qquad \text{...........(4)}$$

Here C_B is the concentration at the boundary and C_o is the original concentration. In the curve representing the probable distribution of ions in cylindrical tube the ordinate at any point may be

Table 2. Negative adsorption measurements of chloride ion in bentonite

Concentration Cl^-		Concentration of the equilibrium solution		m Mass of bentonite in grams	w+w1 Total volume of solution in cc	'V' in cc	$\frac{q}{\sqrt{\upsilon\cdot\beta\cdot n}}$
1.1370	N/20	1.1409	N/20	1.1419	58.96	23.3	13.4
0.7509	N/25	0.7608	N/25	1.2476	53.07	56.0	18.35
0.8201	N/50	0.8361	N/50	1.1571	65.20	107.8	24.83
1.044	N/100	1.1291	N/100	1.1878	73.54	135.6	30.3

written as equal to

$$\frac{C_o.A.dx}{\sigma.\sqrt{2\Pi}}.\int_{\varepsilon}^{\infty} e^{\frac{-x^2}{2\sigma^2}}.dx$$

If C is the concentration of the ion in it we may write it as

$$C.A\ dx = \frac{C_o.A.dx}{\sigma.\sqrt{2\Pi}}.\int_{\varepsilon}^{\infty} e^{\frac{-x^2}{2\sigma^2}}.dx$$

$$\therefore \quad \frac{dC}{dx} = \frac{C_o}{\sigma.\sqrt{2\Pi}}\left[\frac{-x^2}{2\sigma}\right]_{\varepsilon}^{\infty} \qquad \text{.........(5)}$$

where $\frac{dC}{dx}$ is the concentration gradient.

At the origin O, $\varepsilon = 0$

$$\text{Then} \quad \frac{dC}{dx} = -\frac{C_0}{\sigma.2\Pi} \qquad \text{................(6)}$$

Defining the diffusion coefficient D as given below we have

$$\frac{dq}{dt} = -D.A.\frac{dC}{dx} \qquad \text{..................(7)}$$

Substituting the values of $\frac{dq}{dt}$ and $\frac{dC}{dx}$ as obtained in equations (4) and (6) in equation (7), we get

$$\frac{C_o.A.dS}{\sqrt{2\Pi}.dt} = \frac{D.C_o.A}{S\sqrt{2\Pi}}$$

or D . dt = S. dS

Integrating between the times 0 and τ and the corresponding values of the standard deviation between 0 and σ we get

$$\int_0^{\tau} D.dt = \int_0^{\sigma} S.dS$$

$$\text{or} \quad D = \frac{\sigma^2}{2\tau}$$

3. Iso-conductivity Value

Chemical methods of estimating the Cation Exchange Capacity (CEC) are not only time consuming but also dependent on the chemicals used. A physical method based on the charge present on the clay surface was developed and perfected in the Agricultural Physics Division of IARI (Dakshinamurti, 1960). Clay behaves like a salt. When added to water, calcium bentonite splits up into a calcium ion and bentonite particle. The conductivity of the ion and the particle increase the conductivity of water. Same is the case when calcium bentonite is added to an electrolyte also.

In a solution containing $\frac{N}{40}$ KBr or less the bentonite is deflocculated and the suspension exhibits no rigidity. At a critical concentration value of the electrolyte the conductivity of clay electrolyte system remains constant with increasing quantities of clay added to the system. This critical concentration is termed the "Isoconductivity value of the clay". This is the case with soil as well. Extensive work carried out at the IARI Laboratory (Bhavanarayana and Dakshinamurti, 1974; Dakshinamurti and Bhavanarayana, 1982) as well as abroad confirmed the linear relationship between the isoconductivity value and the cation exchange capacity. A theoretical relationship between the Cation Exchange Capacity (CEC) and the isoconductivity value was developed by Kemper (Dakshinamurti and Chandool, 1966) as given below:

Table 3. Relative conductivity of bentonite suspensions in potassium bromide solution at different concentrations

Normality of electrolyte	% weight of Bentonite	Relative conductivity
0.1	0.91	0.836
0.05	1.14	0.924
0.0333	0.76	0.974
0.025	0.57	1.028
0.0167	0.38	1.020
0.0125	0.27	1.037
0.0083	0.19	1.033

Factors contributing to the electrical conductivity (Kg) of a clay gel can be related by

$$K_s = k\left[\frac{\alpha_a}{T_a}.f_a.N_a + \frac{\alpha_e}{T_e}.N_e\right] \quad \text{............(8)}$$

where Ta and Te are tortuosity factors ($\geq$1.0) for the adsorbed and the free electrolyte ions, respectively; α_a and α_e are the relative mobility ($\leq$ 1.0) of the adsorbed and free electrolyte, respectively, as a result of their positions near or away from the clay; fa is the fraction of the adsorbed ions participating in conductivity phenomena (mobile fraction); Na and Ne are the number of adsorbed and free electrolyte ions, respectively, per centimetre of gel; k is the proportionality constant defined by the equation (8).

The number of adsorbed ions per centimetre of gel is

$$N_a = EC \times BD \quad \text{.....................(9)}$$

where EC is the exchange capacity in ions per gram clay and BD is the bulk density of the gel in grams of clay per centimetre of gel

$$N_e = C_e \times \theta = C_e\left[1 - \frac{BD}{\rho}\right] \quad \text{............(10)}$$

where C_e is the concentration of the free electrolyte in ions per centimetre solution; θ is the volumetric moisture content of the gel (centimetres of solution per centimetres of gel); and ρ is the density of the clay (grams per centimetre of clay).

Substituting equations (9) and (10) in (8),

$$K_g = k\left[\frac{\alpha_a}{T_a}.f_a.(EC \times BD) + \frac{\alpha_e}{T_e}.C_e.\left\{1 - \frac{BD}{\rho}\right\}\right]$$

$$= k\left[BD\left\{\frac{\alpha_a}{T_a}.f_a.EC - \frac{\alpha_e}{T_e}.\frac{C_e}{\rho}\right\} + \frac{\alpha_e}{T_e}.C_e\right] \quad \text{.......11)}$$

Experimentally it was found that at some value of $C_e = C_{ei}$, Kg is often nearly constant (K_{iso}) as the bulk density varies. Thus

$$K_{iso} = k\left[BD\left\{\frac{\alpha_a}{T_a}.f_a.EC - \frac{\alpha_e}{T_e}.\frac{C_{ei}}{\rho}\right\} + \frac{\alpha_e}{T_e}.C_{ei}\right] \quad \text{.....(12)}$$

As BD $\rightarrow$ 1.0, α_a and α_e $\rightarrow$ 1.0 and Ta and Te $\rightarrow$ 1.0, and the equation (12) becomes

$$K_{iso} = kC_{ei} \quad \text{..........................(13)}$$

Rearranging equation (12) and substituting $\frac{K_{iso}}{k} = C_{ei}$ from equation (13)

$$EC = \frac{\rho + (BD - \rho).\frac{\alpha_e}{T_e}}{BD \cdot \frac{\alpha_a}{T_a} \cdot f_a \cdot \rho} \cdot C_{ei} \quad \text{.......(14)}$$

or, using the above equation (13), Cei = $\frac{K_{iso}}{k}$

$$EC = \left[\frac{\rho + (BD - \rho) \cdot \frac{\alpha_e}{T_e}}{BD \cdot \frac{\alpha_a}{T_a} \cdot f_a \cdot \rho \cdot k}\right] K_{iso} \quad \text{.......(15)}$$

Apparently the term in the square brackets of equation (15) is the constant factor found experimentally. Insertion of some reasonable relationships between BD, αe/Te and αa/Ta indicates that this term would be fairly constant if fa did not change.

4. Soil Solution

If ordinary water is used as a displacing liquid with slow velocity of movement, the displaced liquid in the first few fractions would be the soil solution. This is what has happened in the experiments of Burd and Martin (1923) in extracting soil solution. Movement of plant nutrients takes place by three processes; viz., mass flow, dispersion and diffusion. As long as gravitational force acts on the soil solution, mass flow takes place. When once the action of gravitational force ceases, the nutrients move only by the process of diffusion. The greatest contribution ever made to Physics by a Biologist is the Poiseuille's law, which states that the flow of fluid through a capillary tube is laminar and the displacement liquid flows through the tube gradually displacing the original solution in the tube. When the velocity of flow of displacing liquid becomes small, then at the boundary of the miscible front, diffusion takes place. The entire process is complicated where diffusion, dispersion and mass flow are combined to explain the movement of plant nutrients through the soil.

Miscible displacement studies were conducted (Bhavanarayana *et al.*, 1982) to partition the contributions of the dispersion and diffusion processes. Dispersion coefficients were determined for nitrate and bicarbonate ions in capillary tubes, sand and soil columns and the various mathematical equations were evaluated for estimating the dispersion and diffusion coefficients. The results showed that the dispersion coefficients and molecular diffusion coefficients were found to be different in different models by several times.

5. Soil Structure

Water moves through the channels that are formed by the soil constituents, namely, sand, silt and clay, and the aggregates that are formed out of these fundamental bricks. The channels shape themselves into different forms by the aggregating agents like organic carbon, biological gums and by the mechanical binding of these particles by the fine root-lets that grow inside. A soil is characterised by the random distribution of the aggregates forming channels with twists and constrictions. This is what is called soil structure. The well-aggregated soil is supposed to have good structure, allowing water and air to flow and roots to penetrate absorbing maximum amount of nutrients from the soil solution. Perhaps there are as many indices of soil structure as there are schools of soil physics. Of the several soil indices that are in practical use, one of the best-correlated ones is the hydraulic conductivity value at compacted minimum bulk density. This index is determined using a simple IARI compactor developed in the Division of Agricultural Physics (Dakshinamurti and Pradhan, 1966) and is being used in all the ICAR scheme centres throughout India.

The highly significant index of soil structure, namely, the hydraulic conductivity at compacted minimum bulk density was used to measure the dynamics of soil structure in a relay cropping, an intensive cultivation technique. Relay cropping is an intensive cultivation technique where 4 crops, in succession, are taken in one year on the same piece of land. Life cycles of all 4 crops put together would exceed one calendar year, as such one crop should hand over the land to the next crop in quick succession. More often the sowing of the second crop would take place in a standing crop heading towards harvest. Two such relay cropping namely (a) wheat-*mung*-maize-toria (b) wheat-*mung*-maize-potato were studied (Prabhakara and Dakshinamurti, 1976). It is observed that the index of soil structure was quite high at the end of every harvest and more so after a leguminous *mung* crop, indicating that the legume should always be introduced into relay cropping. This high amplitude of soil structure was due to about 3,140 kilograms of total root weight contributed by all the 4 crops.

Table 4 gives the results of the bulk density and hydraulic conductivity at compacted minimum bulk density in the first 30 cm of the soil. Percentage organic matter present in the first 15 cm of the soil is also given in the table. These values were estimated from the samples collected after harvesting each of the four crops that were grown in relay-A. In this relay the crop rotation was wheat-*mung*-maize-*toria*. Table-5 gives the results recorded in Relay-B where the cropping pattern was wheat-*mung*-maize-potato.

Table 4. Bulk density, hydraulic conductivity and percentage organic matter present in the soils after the harvest of each of the four crops grown (Relay-A)

Soil No.	Crop harvested	Bulk density (0-30 cm) $g.cm^{-3}$	hydraulic conductivity $cm.hr^{-1}$	organic carbon %
1	Wheat	—	25.2	0.49
2	Mung	1.56	46.9	0.52
3	Maize	1.50	24 5	0.71
4	Toria	1.49	23.6	0.64

Comparison of different structural conditions formed after harvesting each of the four crops grown in an year on the same field in an intensive cultivation experiment (relay croping) indicated the high sensitivity of the structural index in differentiating the structural conditions of the field.

Table 5. Bulk density, hydraulic conductivity and percentage organic matter present in the soils after the harvest of each of the four crops grown (Relay-B)

Soil No.	Crop harvested	Bulk density (0-30 cm) $g.cm^{-3}$	hydraulic conductivity $cm.hr^{-1}$	organic carbon %
1	Wheat	1.60	45.1	0.47
2	Mung	1.58	51.9	0.60
3	Maize	1.51	23.1	0.64
4	Potato	1.47	32.1	0.49

6. Judicious Irrigation for Maximisation of Yields

Studies carried out on soil based irrigation with a given quantity of water have shown that wheat crop in Delhi could give the maximum yields if irrigation is restricted in the root zone to a moisture content equivalent to 3/4 of the field capacity value at each irrigation given. The yields obtained at different amounts of irrigation water between dry condition and 3 times field capacity on a statistically laid experiment with two promising wheat varieties *sharbaty sonora* and triple gean dwarf indicated that 3/4 field capacity of irrigation covering the root zone is ideal (Dakshinamurti and Reddy, 1971).

This restricted irrigation at 3/4 field capacity seems to make most of mineralisable nitrogen available to the root without leaching it down. These experiments show the potential conservation of water for growing crops.

7. pF of Soils

Water is held by the soil with certain energy and the soil moisture potential is merely tension expressed in centimetres of water column. In the year 1935, Schofield suggested to use logarithm of this tension and gave this logarithm the symbol, pF, an exponential expression of a free energy difference based on the height of water column above free water level in centimetres. This tension includes hydrostatic, capillary, osmotic and hygroscopic forces. It is expressed as the logarithm to the base 10 of the numerical value of the negative pressure of the soil moisture expressed in centimetres of water, pF = log h. Two important soil moisture constants useful in soil physics are defined as (1) field capacity and (2) the wilting point. Even though the field capacity value is not the same for all soils, for practical reasons it is still in use. Usually it is stated as 1/3 bar of tension corresponding to a pF of 2.53. Similarly the wilting point corresponds to 14.8 atmospheres and works out as pF = 4.18.

8. Effective Pore Space

Tortuousity experienced in the migration of nutrient ions should be the same whether the measurements are made by diffusion method or by electrical conductivity method in soil beds. The effective fractional areas of cross section measured by these two methods are given in the Fig. 2. These values give the fraction of the pore space that is actually available for the migration of nutrient ions.

The results showed a good accord between the observations of Penman (1940 a,b) obtained by measurements of gaseous diffusion and those of the author (1959) measured by ionic diffusion throughout the region of porosity studied. They fall on a smooth curve which tends to reach a value of P_{eff} = 1 as should be expected when P=1.

The line drawn up to a porosity value of about 0.65 shows a tortuousity factor $\frac{P_{eff}}{P} = 0.7$, as compared to the values of 0.65 recorded by Penman. Above the value of $P = 0.65$, the course of the curve changed, suggesting a change from the non-colloidal to the colloidal size of the particles that constitute the porous bed. In the former, the electrolyte fills the porous bed, while in the latter the solid is suspended in the electrolyte. Effective pore space value depends more on size of pores and shape of particles that build the porous bed than on actual porosity.

B. Concepts of Physics in Agricultural Operations

1. Rice Cultivation Providing Drainage

The phenomenon of thixotropy is successfully used in the puddling of soils for rice. The field usually is puddled with the main view of keeping the water for a longer time without percolating. Rice in fact sown as aquatic crop can grow both under dry land conditions as well as aquatic conditions, because of its capacity of taking oxygen through the stem and passing it on to the roots for their healthy growth. In our country, although rice is grown at all altitudes starting from Kanyakumari to Kashmir, it has been customarized to allow the water to flow from field to field, thus loosing the nutrients from the surface and also not allowing a second dose of fertiliser to be given for its complete utilisation. Every living system has both intake and excretion. In the case of rice plant, excretion of the root system, being toxic, is required to be washed out. This could be done in the case of rice crop by allowing drainage to take place through the root system (Dakshinamurti *et al.*, 1973). Using this principle, rice yields were increased to 6-7 t/ha in Thailand, Philippines, Taiwan, Japan and other rice producing countries, while in India, we are still having a stagnant yield of 2-3 t/ha on an average. It is very essential to take cognisance of this factor and introduce on a large-scale research work on rice production on these puddled lands. Although an attempt was made by ICAR in 1973-74 to carry out this investigation on 2000 hectares of land in each State of Orissa, West Bengal, Andhra Pradesh and Tamil Nadu, for reasons best known to them, this could not be carried out. This work should be taken up in all rice research institutes as well as by the centre.

This work requires (1) stoppage of flow of water from field and (2) introduction of a drainage channel (Habibullah *et al.*, 1977) parallel to the irrigation channel at a lower depth so that the water drained through the root system easily percolates and removes the toxins. Japan's cultivators, in a personal conversation with the author, informed that in their comparatively small sized fields they had sacrificed 10% of the land for drainage purposes and the very high yields of 6-7 tons per hectare thus obtained more than compensated the value of the land alloted for drainage channels.

2. Water harvesting in tanks by bentonite applications

About 75% of our agricultural land is under rainfed conditions. Small tanks are often used in villages. Water stored in the rainy season in these tanks is used for rice or other crops latter. But most of the water infiltrates down. As the water table was quite high at the IARI it was thought desirable to construct suitable tanks on the farm area and pump the ground water into these tanks for further use. Such an attempt is useful only if the bottom of the tank is impervious.

Bentonite when used in conjunction with sodium chloride, and sodium carbonate in varying proportions on sandy loam soils of the IARI farm

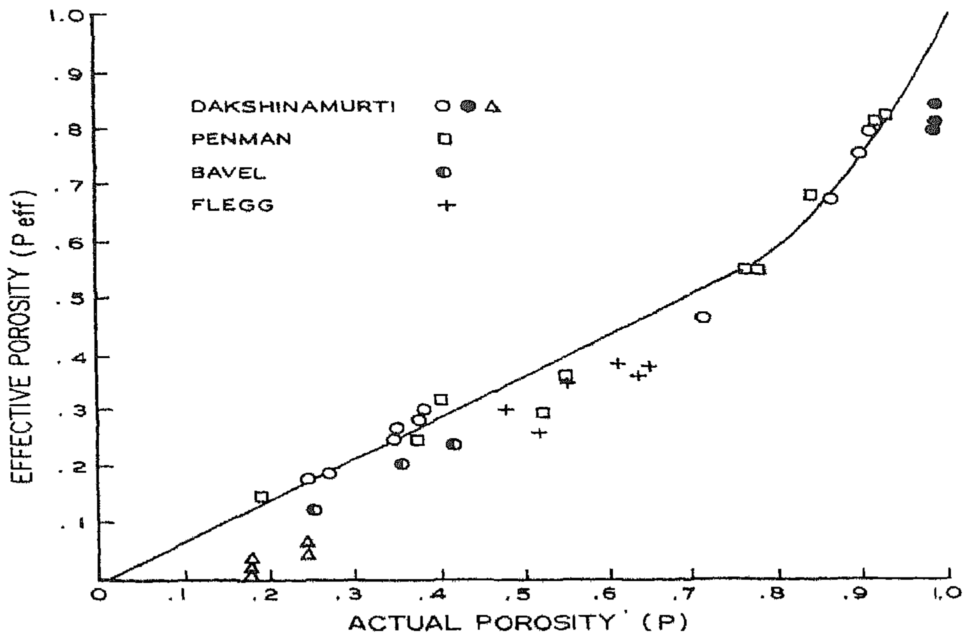

Fig. 2. Actual and effective porosities of porous beds composed of particles of different sizes and shapes

was found to change the physical properties of the soil by reducing percolation losses. Introduction of such mixtures, at the bottom of the tank beds to a depth of 15 cm was found to form a thixotropic gel reducing the infiltration to about 1/10th of the original value thus providing an efficient and effective method of storing water in tanks constructed even on sandy loam soils (Fig.3).

The bentonite technique has a potential application as a soil conditioner (Das and Dakshinamurti, 1975) and in reducing infiltration losses in rice fields as well. Where bentonite is not available, small quantities of black cotton soil rich in montmorillonite can be substituted in such proportions as to keep up the required percentage of clay content value. This technique has a potential application in irrigation systems where the seepage water turns most of the surrounding areas into saline or alkaline soils.

3. Neutron Moisture Meter

Measurement of moisture *in situ* over a large scale in soils is impossible if samples have to be collected from different places. However, physical methods such as neutron moisture measurements that can be carried out with a neutron moisture meter, without disturbing a soil profile, make these measurements simple, expedient and effective. These methods are so rapid that the moisture content can be determined at several places on thousands of hectares of land in one day and proper tilth conditions can be ascertained both in rain fed as well as in dry land agriculture.

Fast neutrons lose energy and are slowed down when they collide with hydrogen atoms. This is specific with water molecules that contain hydrogen. The slow neutrons so formed are caught by a detector and counted by a counting unit. The effective sphere of activity for measurement is a sphere of about 15 cm radius. There is no chance of interaction of fast neutrons with any other substance except organic carbon content of the soils. The *in situ* measurements at different depths can be repeated without disturbing the soil. This is very necessary for determining the best tilth conditions on extensive areas in dry land agriculture.

Installing an aluminum access tube vertically and using a nucleonic moisture and density gauge EIS 659, the moisture contents of the surface soil were measured gravimetrically. Capillary conductivity *in situ* under dry land conditions was determined as to assess the deep percolation and capillary rise components of water balance equation.

4. Ground Water Studies

Ground water occurs in two strata; surface ground water contributed by open wells and deep underground water that is stored some years back in aquifers. In irrigated agriculture a fraction of the

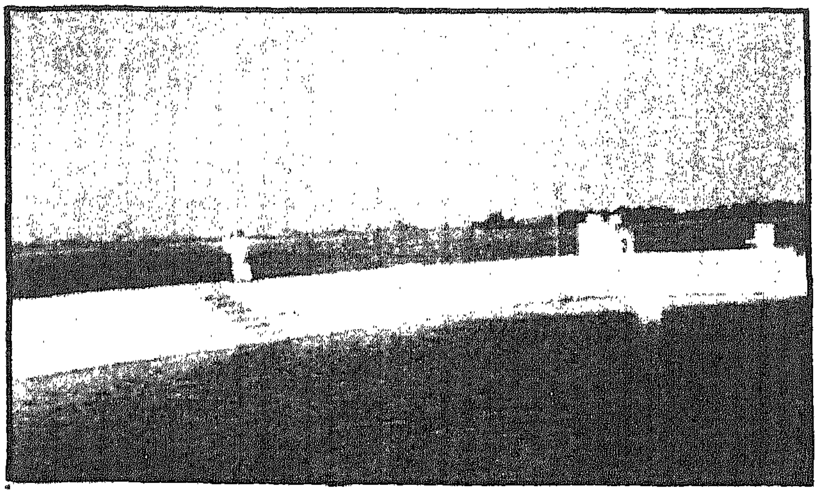

Fig. 3. Water stored in a tank at IARI, using bentonite technique

rainfall (effective rainfall) and another fraction of the irrigated water (effective irrigation) form the surface ground water (Dakshinamurti and Biswas, 1962). If the water table rises nearly upto the surface of the soil, crop growth and fertiliser utility will be affected by the rising ground water. For planning surface drainage the direction and magnitude of the hydraulic gradient should be evaluated.

Analysis of the changes in the water levels recorded for a long period in over 13 wells (unused) and the irrigation water annually supplied to the farm area at the IARI indicated that about 42-57 percent of the rainfall and 9-11 percent of the irrigation water were contributed to the surface ground water. These figures were confirmed by independent field experiments conducted on the farm area (Dakshinamurti *et al.*, 1961).

Equations for determining the direction and magnitude of the hydraulic gradient of the ground water flows were deduced using water levels of three neighbouring wells in static condition. Using these equations the ground water movements in the farm area for over twenty years were traced and drainage requirements were deduced Rao *et al.*, 1963).

5. Radio Isotope Techniques

Radioisotopes and radiation techniques are freely used at the IARI for different purposes with a view to obtain a) high yielding mutants and b) studies on root growth, irrigation and other phenomena. IARI is provided with a Gamma Garden (Cobalt source) where crops grown on the field are exposed to known quantities of cobalt radiation.

Significant root pattern differences were obtained using ^{32}P with plant injection techniques in 6 high yielding wheat varieties namely Sonora 64 (2 gene dwarf), Lerma Rojo (1 gene dwarf), C.306 (tall), Agra local (tall), N.P. 718 (tall) and N.P. 880, grown under identical field conditions in a sandy loam soil of the Indian Agricultural Research Institute. These methods are also used for the quantitative estimation of roots without pulling out the plant from the soil.

6. Physical Methods for Clay Analysis

Clays are crystals with platy structure, arranged in layers with water molecules in between. Electron microscopic studies gave a clear shape of these particles. For these studies the clay crystals are oriented by drying them on a collodin film. The shape, area and even the thickness of the crystals can be determined. Scanning electron microscopes are developed for the direct observation of colloidal clay particles. Crystallographic studies by X-ray methods revealed the entire structure of the clays.

Thermal Methods: Water is embedded between different layers of clays and is bound with different forces. When heated, this water is given off at different temperatures. The water that is present can be either constitutional water or adsorbed water. By heating the clay samples the moisture losses can be estimated. The resulting curves for the main types of clays are quite distinct and thus can be used in the identification of the major types of clay. For example, kaolinites give most of the hydroxyl water around 550o. While the inter layer water of montmorilloniotes is given off between 150o and 250o.

7. Electro-neuro Physiology

This is a branch of science, which was initiated at the Indian Agricultural Research Institute as a joint project between the Division of Agricultural Physics and Entomology. Most of the insecticides that are in use are neurotoxins and none of these toxins is fully understood as regards its biological activity. The toxicity and specificity of these insecticides can be estimated with this new technique of neuro-physiological studies (Singh et al., 1972, 1973) The essential principle of this technique is that when any part of the body is subjected to a stress, neurones at the nerve ends there get excited and emit electrons that move over the nerves. This is similar to the movement of current through a conductor and is therefore subjected to a potential difference between any two points on the nerve. This potential difference is suitably magnified to feed to a cathode ray oscillograph which will be recorded as a line perpendicular to the axis. Such nerve potentials can be measured only when the chamber in which the instrument and the specimen are located is free from electrical and magnetic noises.

Extensive investigations carried out at the Indian Agricultural Research Institute resulted in enabling the interpretation of these results in terms of the known scientific theories.

C. Agricultural Meteorology

1. Micro and Macro Climates

Plants grow under natural climate, called macroclimate, and respond to rainfall, humidity and temperature. As they grow, they produce their own climate in the surroundings called microclimate. The forests, roadside plants and agricultural crops grow and develop under the influence of both macro and microclimates.

Influence of these climates over the growth and yield of wheat crop grown on nine different days of sowing between October 1st and December 20th, in three consecutive years at the Indian Agricultural Research Institute indicated that all the agronomical characters including the grain yield are significantly high in crops grown between 31st October and 20th November. The difference in humidity between the macro and micro climates has been significant in all the nine sowings while the difference in temperatures was significant only for the sowings where the growth and yields were heavy. Then it is possible to predict bumper crop yields in advance if the micro and macro temperatures are measured only for a couple of weeks just after the ear emergence period (Singh et al., 1957).

2. Drought Condition

Occurrence of droughts is a common character in Indian agriculture. A significant correlation is obtained between the extent of drought periods and crop yields (Sastri, 1978, 1984). Preservation soil moisture in deeper layers is necessary for growing at least two crops in drought prone areas. Moisture studies made in sandy loam soils of the IARI indicate the potentialities for combating to some extent the drought conditions by improving the structure of the surface soil and adopting cultural practices for early infiltration of the rainfall. Percent moisture at 15 to 22.5 cm depth under different methods of ploughing are recorded as below.

Moisture conditions under deep ploughing are significantly the same as under fallow for a depth of 5 cm and below. Thus deep ploughing once in three years at least is a good practice in drought prone areas (Dakshinamurti, 1967).

3. Evaporation

Evaporation of water from open dams, irrigation tanks and crop canopies etc. is considerably high under tropical conditions in India. Several meteorologists attempted to deduce equations connecting evaporation and other meteorological factors. The equation deduced by Penman (1948) stood all the tests and enabled the calculation of evaporation from open water, bare soil and grass. Studies conducted at IARI under advective conditions as experienced in north India showed that the value of ET calculated varied from Penman's values by about 30-35% (Sastry and Chakravarty, 1976)).

In marginal rainfall areas it is hard to predict the crop yields. Under such conditions the distribution of Moisture Availability Index (MAI) and its probability of occurrence between threshold yield values (0.5-0.9) guides in predicting potential crop yields (Victor et al., 1982).

Dynamic crop simulation models are being developed for crops grown under different agroclimatic conditions. BRASSICA model developed in the Division of Agricultural Physics was observed to simulate growth and yield of mustard grown under potential conditions. This model is now being tested for its significance at different centres in India (unpublished).

Table 6 Percent Moisture Content of Soils in October 1967

Soil depth cm	Treatments				
	Deep ploughing	Mould board ploughing 20 cm	Desi ploughing 10 cm	Discing 10 cm	Fallow
0-7.5	6.66	5.11	3.44	2.16	9.01
7.5-15	9.52	7.64	7.66	4.51	9.69
15-22.5	10.49	8.75	7.60	6.76	9.33
22.5-30	11.17	8.84	8.04	7.31	11.20
30-37.5	11.49	8.87	8.25	6.96	13.22

D. Use of Frontier Technology

1. Remote Sensing Technology

Everything in nature absorbs, reflects or emits some type of electromagnetic radiation. These radiations are different for different objects and they are called the signatures or fingerprints of these objects. Remote sensing of the environment has thus became an elegant tool for solving several problems in agriculture. This technique started in 1968 at the Division of Agricultural Physics of the I.A.R.I., is now being taken up at several centres in India.

Coconut wilt disease causing a loss of about 10 million rupees per annum in the Kerala State was taken up. Thirty percent of the population of Kerala is dependent on this industry. Since 1968 this division represented India at several International symposia on studies of remote sensing on the coconut wilt disease (Dakshinamurti et al., 1971). Several scientists of the Division of Agricultural Physics are today engaged in solving agricultural problems using remote sensing techniques. This subject is included in the Post Graduate curriculum of the Agricultural Physics Division and scientists all over India are being given special training in this field.

2. Spectrographic and Spectrophotometric Techniques

There are a number of elements such as Manganese, Iron, Copper, Boron, Molybedenum, Zinc etc., which are absolutely necessary though required in micro quantities for a healthy growth of plant. These microelements can very rapidly be estimated both in soils and plants by spectrographic methods.

3. Cathode Layer Arc Technique

In an arc discharge the potential gradient is very high near the cathode. Here the cations get accumulated considerably emitting their characteristic radiation. Mannkopff and Peters (1931) in Germany took advantage of the cathode layer arc technique and estimated the microelements.

This technique perfected in the Agricultural Physics Division (Dakshinamurti and Ramamoorthy, 1953) was used in the ICAR Citrus Die Back Scheme in Coorg and in several other estimations in soils and plants.

Study of microelement status in soils at different pH values ranging from 4.5 to 8.5 indicated the accumulation of these elements at the extreme values of pH. These results are explained due to the sorption properties of hydroxides of iron and manganese (Dakshinamurti and Mittal, 1962).

Several physical equipments such as mass spectrometer in the estimation of the soluble isotope ^{15}N and nuclear magnetic resonance in the estimation of oils (non-destructive method of estimation) in oil seeds are useful both in soil and plant research.

4. Absorption Spectrometric Studies

Several plant and animal products can be estimated by absorption spectrographic techniques. A sensitive technique developed for the estimation of nicotine (Ramamoorthy et al., 1952) clearly established that the root system is of primary importance in its specificity of producing nicotine alkaloids in tobacco - tomato grafts.

It is evident from the above that almost all the branches of physics play significant role in the development of Agriculture. Where there are irrigation facilities available and availability of plant nutrients is no constraint modern technology helps in increasing the yields. In a country like India where 75% of our agriculture is rain fed, water harvesting, storage and judicious irrigation techniques are required to be strengthened as to grow "More crop per drop".

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